INVESTIGATION OF SOIL HYDRO-STRUCTURAL PARAMETERS UNDER VARIOUS SOIL MANAGEMENT PRACTICES AND FEASIBILITY OF DEFINING A SOIL QUALITY INDICATOR: A CASE STUDY

A Thesis

by

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ABSTRACT

Hydrostructural parameters are derived from continuously measured thermodynamic relationships which characterize the soil aggregates. The soil aggregate structure is unique and dynamic for each soil type and can be affected by the soil's physical, chemical and biological properties. These parameters represent soil behavior and dynamically represent the changes in the soil aggregate structure with time. It can be used for developing a good quantitative indicator for the soil health. This study involves a field experiment to examine the changes in pedostructure-based soil characterization under different soil management methods and definng a new soil quality indicator. Three organic treatments (chicken, dairy manure and milorganite) were applied at 0, 168, 336, 672 kgN/ha (rate labeled 1,2 and 3 respectively) for 36 plots with size 10 ft. × 5 ft. After extracting 12 hydro-structural parameters from TypoSoil measurements, statistical analysis evaluated the sensitivity of these parameters to changes in the soil management across the treatments.

Results showed that increasing the rate of application from 1 to 3 didn't show significant effects on hydrostructural parameters for any treatments. However, regardless of the type of treatment, management application significantly enhanced water content and available water in A horizon. In B horizon, only rate-3, affected available water for Chicken and Dairy manure. In the comparison between three treatments, the dairy manure has more obvious effects and is promising to improve soil aggregate structure for rates more than rate-1. Also, best application rate for chicken manure seems to be for treatment rate-1, for dairy manure, rate-2 and for milorganite rate-3.

There are two reasons that developing a comprehensive soil quality indicator was not possible at this stage of the experiment. First, only sensitive parameters to different management (rate or treatment) were water content parameters but direct aggregate structure parameters didn't change across treatments. Therefore, the soil quality indicator model with these parameters would not be all-inclusive. The short duration of the experiment (6 months) can explain the lack of change in the aggregate structure. However, adding the organic matter helped to increase the potential energy of holding the water and thus increased the water available capacity. Second, there are some other parameters such as crop yield and organic matter which could enhance small changes in aggregate structure parameters and make interpretations easier. These measurements and analysis are parts of research being conducted by Prairie View University researchers and results have not published yet.

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1. INTRODUCTION

Testing and inspection of soils response to agricultural management practices over time helps deciding if the method sustain or enhance soil quality. Traditionally, the productivity of soil is the main variable in definition of the soil quality (Hornik 1992), whereas more recently, the principal engagement of the soil in crop production and also in water and atmospheric refinement has been acknowledged, thus highlighting the function of the soil both for production and for environmental quality (Gil-Sotres, F., et al. 2005).

Soil health (soil quality index) is among the common indicators for evaluating the behavioral performance of an agriculture production system. The main reason of defining soil quality index is to instruct farmers and land owners about soil management methods effect on their farm soil functionality (Bünemann, E. et al., 2018). Defining a decent comprehensive and universal soil quality index is not possible because of variety of factors affecting soil quality such as: parent material, climate, topography and hydrology (Bünemann, E. et al., 2018). In other words, soil quality depends on wide range of chemical, physical, biological and biochemical properties; therefore, to make it significant, defining the soil quality index requires the determination of the properties most sensitive to differences in management practices (Yakovchenko et al. 1996). Its evaluation requires to combine baseline or indicating values to allow investigate the management method outcomes through a set of sensitive soil properties. These soil properties should reveal the capacity of a soil to function and can be applied as indicators of soil quality.

Currently, there are two primary approaches to study soil health: (1) The indicator-based approach is the "standard" method in which assessment of soil quality uses either qualitative or quantitative indicators, (the physical, chemical, or biological properties, processes, or characteristics of the soil medium) (USDA NRCS, 2015); and (2) The management-based approach with assessing soil properties (i.e. indicators), but by concentrating on the effects of management we expected, to establish a more consistent framework for the soil quality concept (Schjønning et al., 2004). While both approaches are needed to assess soil quality, the indicator-based approach is more universal and uses relatively easily accessible data. The management-based approach offers a framework for understanding the soil quality concept and is more related to specific management practices, and thus it is more site and soil function specific. The management approach could be more favourable when considering the need for a more accurate assessment of management practices on soil quality and the variability of soil, climate, and practices across the globe. Both approaches are needed to assess the soil quality; However, both approaches lack two important aspects: (1) the quantitative assessment of the human practices on soil aggregate structure (the soil hierarchical organization at aggregate scale) due to the lack of representative and measurable parameters that describe this structure and its hydraulic functioning; and thus (2) limiting the ability to predict the future behavior in soil functions that are related to soil structure. And these are major functions including: regulating water, solute and air movement through soil; the ability to sustain life; cycling and storing nutrients; and performing other vital functions. Making these quantitative-based predictions possible opens the door for more focused solutions to the urging question about the long-term impact of our practices nowadays on the future quality of this valuable and non-renewable natural resource, and thus our food security.

In this scope, researchers have proposed a various combination of soil properties out of almost 81 potential properties as the soil quality indicator using selection rules, based on a precise outline of the required ecosystem service(s) or management purpose(s) to be directed. Also, there are many complex and novel methods which are promising for future soil quality evaluation designs (Bünemann, E. et al., 2018). Since the index should help farmers and land managers not scientists, minimized dataset, ease of sampling, sensitivity to even small management changes in the scale of the farm and ease of interpretation should be considered in the soil quality index determination method.

On the other hand, in common soil quality indicators, changes in each parameter highly correlated to other parameters or process variations, e.g. dependence of microbial biomass or soil organic carbon on soil texture (Candinas et al., 2002; Johannes et al., 2017). Therefore choosing the property of soil that integrates physical, chemical and biological properties all included can guarantee easiness and conciseness of defining a comprehensive soil quality indicator.

To consider the role of soil aggregate structure, as an integrated representative indicator of soil health, pedostructure concept will be used in this project. Braudeau et al. (2004) introduced the pedostructure "soil aggregate structure" concept to highlight the role of soil aggregates in characterizing and modeling the water flow in soil medium. The concept is based on Brewer (1964) pedological description of the level of soil organization starting from primary particles (silt, sand, clay, organic matter) to primary peds to aggregates to soil structure to soil horizon to pedon. Brewer provided imperative qualitative data about the soil organization, but not how it functions and interacts with water and air. Therefore, Braudeau and Mohtar (2004) completed this missing interaction by using the soil shrinkage curve. Soil shrinkage curve (ShC) is a soil-water characteristic correlation between the soil water content and the soil specific volume (which is a characteristic of Brewer description of soil organization). The coupling of Brewer qualitative description of soil medium and levels of the organization with the soil shrinkage curve was given the name of pedostructure concept.

Braudeau et al., (2014; 2016) and Assi et al. (2014) described and outlined the process of characterizing the pedostructure through a set of thermodynamic parameters, state variables and governing equations. They gave the name of “hydro-structural parameters” to the parameters that describe the pedostructure (soil aggregate structure and its interaction with water) of a soil horizon. Given that: (1) soil aggregates structure can be affected by the soil physical, chemical and biological properties, (2) these hydro-structural parameters are characteristics of the soil aggregate structure and they are unique for each soil types; and (3) these hydro-structural parameters are physical measurable parameters that can be used to track the changes in the soil aggregates structure, pedostructure concept and its hydro-structural properties can be used in developing a good quantitative indicator for soil health.

2. OBJECTIVES

The overall objective of this study is to investigate soil hydro-structural parameters under different soil management practices and the ability to develop a quantitative indicator of soil health using the pedostructure concept.

Specifically, this research will:

(1) Determine the soil-water holding properties “saturated water content, field capacity, permanent wilting point, and available water” of a sandy loam soil under different manure types with different application rates.

(2) Apply sensitivity analyses to identify the most significant parameters in the studied soil affected by the application rate and type of treatments change in order to compare effectiveness of treatments in different rates and also develop a quantitative soil quality indicator.

3. LITERATURE REVIEW

3.1. Soil quality indicator literature review

Soil potential for agricultural production has traditionally been the main interest in soil assessment. The history of these assessments goes back to "even before the evidence of written records. Documentation can be found in Ancient Chinese books such as "Yugong" and "Zhouli", written at 2070–1600 BCE and 1048–256 BCE, respectively" (Harrison et al., 2010), and in the work of Columella, a Roman authors at 4–70 A.D. (Warkentin, 1995). In the term of definition, first soil quality for agricultural production was captured in soil fertility definition that is documented in German crop yield science literature (Patzel et al., 2000). Since soil fertility concept embodies only soil properties that have an effect on crop yield, other more broad concepts evoked. The next concept was land quality as one of earliest examples, combines features of the soil, water, climate, topography and vegetation (Carter et al., 1997; Dumanski and Pieri, 2000) with the goal of land assessment for various uses. The land quality was investigating fertile land for agriculture in lands with low population densities, but in the highly populated area, its concern was enhancing existing farms in particular by manuring (van Diepen, et al., 1991).

The term of soil quality has been introduced by Mausel (1971) for the first time, however, it has sometimes been used under the land quality definitions (e.g. Eswaran et al., 1997). Developing through several decades the broadest definition for soil quality as "the capacity of a soil to function within the ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran and Parkin, 1994 1996). The same broad meaning of soil quality was already employed by Warkentin and Fletcher (1977). The significant difference between soil quality and land quality and land evaluation is that soil quality consider dynamic soil properties which can be thoroughly controlled by soil management and their main interaction zone is in the surface horizon (0–25 cm) of the soil (Karlen et al., 2003).

“Soil health” has been used correspondently with soil quality. Soil health term applies when soil quality effects animals and human’s health (e.g. Warkentin, 1995). Indeed, soil quality mostly highlights the soil's capacity to be productive for a particular crop, while soil health centres more on the soil's continued capability to maintain plant growth and preserve its functions (Bünemann, et al., 2018). After some debates about soil quality vs. soil health outlines in the 1990s, scientists agreed that these two terms can be used synonymously because of major overlap they share.

There were also two terms in the body of soil quality concept that there were debates about their applying in determinations; "Services" and "function". The first answers to "what is" (inherit properties) and the second responses to "What can be" (management) questions based on soil capability (Bouma et al., 2017). Baveye et al. (2016) argue that different views of soil in ecology result in the tendency to neglect sometimes soil ecosystem services or sometimes its functionality. Finally, as a comprehensive definition, according to Glenk et al. (2012), “soil functions as (bundles of) soil processes that underpin the delivery of ecosystem services". This definition can address the gap between soil statics and dynamics for any objective related to yielding soil functions (Bouma et al., 2017).

The history of soil quality measurements is rooted in either intrinsic soil characteristics measurement or impacts of human management. Mausel (1971) measured soil quality based on its ability to yield some cereals under high-level management. Later, Larson and Pierce (1991) explained complexity of concentrating on agricultural fertility and recommended to separate soil quality from crop yield. Doran and Parkin (1994) sought a definition of soil quality that stresses soil contribution to environmental quality besides productivity. However, the concept of soil quality by Doran and Parkin (1994) was profoundly criticized in several papers mainly because of their definition bias towards certain soil types and a limited number of crops that provide cheap food resulted from a focus on intrinsic properties of the soil. But it was a start for management to become the central issue: after that weight for productivity has declined in soil quality definition, global indexes have recognized for trade-offs and the role of stakeholders who manage soils (owners, farmers, policymakers, etc.) gained more weights in the definition. (Bünemann, E. et al., 2018).

Throughout the history of soil quality assessment, various soil quality indicators have been designed among physical, chemical and biological properties of soil. The selection of soil quality indicators requires mechanistic linkages among indicators and soil functions or ecosystem services (Creamer et al., 2016) but infrequently firmly set among empirical validation (e.g. van Eekeren et al., 2010). Giving up on looking for a one-size-fits-all description for soil quality indicator, today, at least one conceptual condition is defined for the definition of soil quality indicator and its goal is to analysis a particular soil function or (Bünemann, E. et al., 2018).

Literature of optimization of soil quality indication emphasizes ease of sampling and measurement besides being reliable and cost-effective (Idowu et al., 2008). Sensitivity to changes in management is also discussed repeatedly. Comparability to the results of other quality indicators studies (Morvan et al., 2008) and clear interpretation schemes are desired as well. Another consideration is that increasing the number of indicators will increase interpretations complexity. Plus, especially in the case of biological parameters measurement costs go up (O'Sullivan et al., 2017). Because of these, the reduction of indicators will be analyzed on a set of samples should be minimized and this selection needs expert judgment (e.g. Doran and Parkin, 1994).

Data reduction gets help from statistical analysis of indicators by multiple correlation or multiple regression (Kosmas et al., 2014) and finally, typically 6 to 8 indicators will be selected. Sometimes expert judgement adds to calculated results and selects one or two more highly correlated soil properties (Sparling and Schipper, 2002).

Looking through publications examining soil quality indicators, in most of them at least one indicator of each category (physical, chemical and biological) is involved. Despite, “soil biological indicators were missing from 40% of the reviewed minimum datasets. Most physical indicators have been used are related to water storage and among chemical indicators, soil organic carbon content, pH, available P and K, total N were proposed more frequently. Likewise, soil respiration, microbial biomass, N mineralization and earthworm density were more common among the biological indicators” (Bünemann, E. et al., 2018).

Barrios said (2007) “Soil organisms play a central role in soil functioning. Therefore, adding biological and biochemical indicators can greatly improve soil quality assessments”. Furthermore, “the evaluation of biological indicators of soil quality is not enough extensive to connect abiotic soil properties that controlling soil functions in terms of biochemical and biophysical transformations and aboveground vegetation performance” (Lehman et al., 2015). Although, at this time, soil biological indicators are mostly limited to measurements of microbial biomass and soil respiration. This condition is unfavourable because soil biota is recognized as the most sensitive indicators of soil quality because of its high responsiveness to changes in environmental conditions (Bastida et al., 2008; Bone et al., 2010; Kibblewhite et al., 2008a; Nielsen and Winding, 2002).

3.2. Pedostructure theory literature review

The pedostructure concept is a new paradigm of soil characteristics that defines soil behaviour based on its aggregate structure. “The various particles of soils are organized and arranged together in a weak and complex spatial network commonly called the soil aggregate structure” (Colleuille, et al., 1996) and according to pedostructure theory, “soil aggregate structure is a unique property for every soil and contributes to all the aforementioned properties” (Mallory, et al., 2011). The development of the pedostructure concept (Braudeau and Mohtar, 2004, 2006; Braudeau et al., 2004) can guide to a reliable perception of soil–water functions across spatial scales. While many investigations have been initiated to determine the impacts of land management on regular soil physical, biological, and chemical properties, no such studies have been done concerning the pedostructure concept (Mallory, et al., 2011) and introducing such an indicator for soil quality will be fill the gap between common soil physical, chemical and biological indicators.

Hydro-structural pedology, if it can be used to define a new soil quality indicator, is able to enhance physical properties assessment by considering different structural organizations and different pore volumes and thermodynamic interaction between them which all perform a significant part in water circulation and distribution inside the soil matrix. On the other hand, soil hydrology controls a diversity of soil physical, chemical and biological processes that drive to the form various soils and several land uses. Following water dynamics and soil aggregate structure detection, chemical transport and interactions would be interpreted as well. Colleuille (1993) has shown that aggregate size as a main unit of soil structure is considerably dependent to chemical characteristics of soil such as salt, while same mineralogy and texture exist. Aggregate formation and water pathways also result from biological activities such as animal burrows, wormholes, decaying roots and insects, etc. Therefore, it is hypothesized that pedostructure analysis can be used to develop an integrated soil quality indicator which can overcome the weakness of discrete analysis of soil properties while including biological interpretation and also minimize the soil quality indicator database.

Traditionally, pedologists have concentrated on field soil profiles (pedon) as recognized in the landscape, soil physicists have maintained theoretical studies and lab examination working on small soil samples, and hydrologists have most often been involved with landscape or watershed scale observations. There is also a clear difference between the methods of studies among these disciplines. In recent literature since pedologists, soil physicists, and hydrologists share many mutual interests and have mutually benefited from each other's research, a synergy formed by linking these three disciplines. For example, Nielsen et al. (1998), explaining the emerging technologies for scaling homogeneity in pedology, related to field spatial and temporal soil water behaviour. Wilding t et al. (1994) also pointed out that classification of soil macro- and micromorphology should be considered in models of soil porous systems describing flow and transport phenomena. Throughout collaborative works on soil physicists and pedologists, Quisen berry et al. (1993) proposed using soil surface texture, subsurface clay mineralogy, and subsoil structure in soil classification scheme, to describe water movement and chemical transport through soils in South Carolina. Lin et al. (1996, 1997, 1998), Vervoort et al. (1999), Shaw et al. (2000), and others in joint works by pedologists, soil physicists, and hydrologists have demonstrated close bonds between soil structure and preferential flow. Consequently, hydropedology emerged as a new paradigm of integrated soil and water science that is evaluated considering time factor. It works as a bridge to integrate the pedon and landscape paradigms with phenomena occurring at microscopic (e.g., pores and aggregates), mesoscopic (e.g., pedons and catenas), and macroscopic (e.g., watersheds, regional, and global) scales (Henry, 2002).

But there is a basic part of soil system that hydropedology cannot approach: the relation among pedology and soil water physics inside the internal structure of the organized soil medium (thermodynamic interactions between the internal soil structure, the soil water, and the soil air). During a project to build a Spatial Information System for irrigated soils in Tunisia, Braudeau et al. (2002) used a systems approach (SA) to mechanistically represent and model the soil by utilising an old pedological map produced in 1963, and the new theory of pedostructure and hydro-structural characterization. In this theory, hierarchies inside the soil organization have been recognized and new descriptive variables of the soil structure characteristics were produced and introduced into the equations defining the physical soil characteristics. Braudeau et al. (2002) revealed that by working within a Systematic Approach (SA) framework, "The functional levels of the internal and external organization of the studied system, i.e., the soil and its environment, can be investigated, defined and characterized". Thus all characteristic variables, functions, and parameters for each scale, as well as the transfer function across scales, are considered in this framework. This new "system view" became the basis of the pedostructure, and offers a physical description and characterization of the soil's internal organization (Braudeau et al., 2004). Braudeau et al. (2005) explained that the pedostructure characteristics can be practised to identify soil type according to their hydro-functional characteristics which are compatible with the pedo-genetic classification (Salahat, 2012).

After 2002 Braudeau, other scientists have developed, evaluated and examined the theory and application of the hydro-structural pedology. For example, Braudeau et al. (2004) demonstrated the link between tensiometric curve with some of the pedostructure variables and the shrinkage curve (Braudeau, et al., 2004). (Braudeau, Frangi, et al., 2004) presented the method of obtaining pedostructure model parameters from Soil Shrinkage Curve using soil core samples with radius and height of 2.5 cm. (Braudeau et al., 2006) added swelling curve into interaction with other predictor parameters of pedostructure model. Martin et al., (2005) developed the computer model based on thermodynamic equilibrium defined in the theory of hydro-structural pedology. Salahat et al.,(2012) presented a methodology to generate and define functional soil mapping units that possess physical and quantitative parameters. Then several management case studies examined by the new terminology; Mallory et al. (2011) evaluated the effect of tillage on soil structural properties using the pedostructure concept. Sonja et al., (2018) studied the impact of different water quality “rainwater, treated wastewater, and brackish groundwater” on the soil water holding properties.

4. THEORETICAL FRAMEWORK

4.1. Hydro-structural pedology theory

4.1.1. Pedostructure concept

The pedostructure concept will be used in analyzing the dynamic in soil hydro-structural properties (Braudeau et al., 2004; Braudeau and Mohtar, 2006, 2009). Figure 2 represents the pedostructure state variables and parameters. To the left is a standard undisturbed soil core ((r=5cm, h= 5cm) ~ 100 cm^3) representing the pedostructure (soil natural aggregates organization) of the soil horizon. To the right, the characteristic parameters of the two water pools of this aggregates structure, micro- and macro-pore domains. Using these water pools and their content changes at various water potentials, fundamental relationships were developed and applied to predict water flow (Braudeau and Mohtar, 2014b).

In the pedostructure characterization laboratory at TAMU, the soil cores have been analyzed following the procedures outlined in Assi et al., (2014) and Braudeau et al., (2016). The analysis will include extracting a set of hydro-structural parameters. The unique characteristics of these parameters are that each represents specific hydro-structural properties of the soil-water system, they are physical parameters (with value and unit of measurement), and they are parameters of the thermodynamically derived equations that consider the soil aggregation and structure (Braudeau et al., 2014).

4.1.2. Thermodynamic formulation of pedostructure characteristic curves

Hydro-structural parameters are characteristics of the water retention curve (WRC) and the soil shrinkage curve (ShC) as formulated by Braudeau et al. (2014). Key to these curves is the fundamental nature of the thermodynamic equations, the state variables (Table 1) used in the equations, and the meaning of their parameters (Table 1). The water contained in the pedostructure which is illustrated in the SREV paradigm as a thermodynamic system describing the soil medium at its first levels of structure: those of the primary peds and their collection. It's why we could distinguish two forms of the water in the soil matrix: one (W_{mi}) buried in the other (W_{ma}), related to the intra and inter- primary peds. Primary peds match to the first level of aggregation of clay particles. According to Braudeau et al. (2014), at the thermodynamic equilibrium between the two water pools, water retention inside and outside the primary peds is the same, such that water retention measured by the tensiometer, h^{eq}, can be modeled as:

$$h^{eq}(W) = \left\{ \begin{array}{ll} h_{mi}\,(W_{mi}^{eq}) = \rho_w \bar{E}_{mi}\left(\frac{1}{W_{mi}^{eq}} - \frac{1}{W_{miSat}}\right), & \textit{inside the primary peds} \\ h_{ma}\,(W_{ma}^{eq}) = \rho_w \bar{E}_{ma}\left(\frac{1}{(W_{ma}^{eq}} - \frac{1}{W_{maSat}}\right), & \textit{outside the primary peds} \end{array} \right\} \quad (1)$$

where W is the pedostructure water content excluding the saturated interpedal water $[\mathrm{kg_{water}\,kg_{soil}^{-1}}]$, W_{ma} gravimetric macropore water content "outside the primary peds" $[\mathrm{kg_{water}\,kg_{soil}^{-1}}]$, W_{mi} gravimetric micropore water content "inside the primary peds" $[\mathrm{kg_{water}\,kg_{soil}^{-1}}]$, $\bar{E}_{ma}$ is potential energy of surface charges positioned on the outer surface of the clay plasma of the primary peds $[\mathrm{J\,kg_{solid}^{-1}}]$, $\bar{E}_{mi}$ is potential energy of surface charges positioned inside the clay plasma of the primary peds $[\mathrm{J\,kg_{solid}^{-1}}]$, h_{mi} is the soil suction inside the primary peds [dm ~ kPa], h_{ma} is the soil suction outside the primary peds [dm ~ kPa], ρ_w is the specific density of water [1 $\mathrm{kg_{water}\ dm^{-3}}$].

Accordingly, at the point of thermodynamic equilibrium, the soil suction measured by the tensiometer,h^{eq}, corresponds to both potentials, such that: $h^{eq} = h_{mi} = \ h_{ma}$, implying the division of W into the two water pools ($\mathrm{W_{ma}}$ gravimetric macro-pore water content "outside the primary peds" [$\mathrm{kg_{water}\ kg_{soil}^{-1}}$], and $\mathrm{W_{mi}}$ gravimetric micro-pore water content "inside the primary peds" [$\mathrm{kg_{water}\ kg_{soil}^{-1}}$]). These water contents at equilibrium are the solutions to a quadratic equation, derived as a function of W that is the pedostructure water content [$\mathrm{kg_{water}\ kg_{soil}^{-1}}$], such that:

$$W_{ma}^{eq}(W) = \frac{\left(W+\frac{\bar{E}}{A}\right)+\sqrt{\left[\left(W+\frac{\bar{E}}{A}\right)^2-\left(4\frac{\bar{E}ma}{A}W\right)\right]}}{2} \tag{2a}$$

and

$$W_{mi}^{eq}(W) = W - W_{ma}^{eq} = \frac{\left(W-\frac{\bar{E}}{A}\right)-\sqrt{\left[\left(W+\frac{\bar{E}}{A}\right)^2-\left(4\frac{\bar{E}ma}{A}W\right)\right]}}{2} \tag{2b}$$

where, A is a constant, such that: $A = \frac{\bar{E}_{ma}}{W_{maSat}} - \frac{\bar{E}_{mi}}{W_{miSat}}$, $\bar{E} = \bar{E}_{mi} + \bar{E}_{ma}$ and $W_{miSat}\ and\ W_{maSat}$ are the micro and macro water content at saturation such that $W_{Sat} = W_{miSat} + W_{maSat}$.

According to Braudeau et al. (2004), the soil shrinkage curve is derived such that:

$$\bar{V} = \bar{V}_0 + K_{bs}w_{bs}^{eq} + K_{st}w_{st}^{eq} + K_{ip}w_{ip} \tag{3}$$

where, $\bar{V}$ is the specific volume of the pedostructure [$dm^3\ kg_{soil}^{-1}$], $\bar{V}_0$ is the specific volume of the pedostructure at the end of the residual phase [$dm^3\ kg_{soil}^{-1}$], $K_{bs},\ K_{st},\ and\ K_{ip}$ are the slopes of the shrinkage curve segments between the inflection points of the measured shrinkage curve and represents the basic, structural, and interpedal linear shrinkage phases, respectively [$dm^3\ kg_{water}^{-1}$], and $w_{bs},\ w_{st},\ and\ w_{ip}$ are the water pools associated to the linear shrinkage phases of the pedostructure in [$kg_{water}\ kg_{soil}^{-1}$] (Figure 1).

The values of the water pools associated with the basic shrinkage phase (w_{bs}), the structural shrinkage phase (w_{st}), and the interpedal shrinkage phase (w_{ip}) can be determined as shown in equations (4-6) (which can also be calculated from equations (2a,b)):

$$w_{bs}^{eq} = W_{mi}^{eq} - w_{re} = \frac{1}{k_N}\ln\left[1 + exp\left(k_N\left(W_{mi}^{eq} - W_{miN}^{eq}\right)\right)\right] \tag{4}$$

$$w_{st} = W_{ma}^{eq} = W - W_{mi}^{eq} \tag{5}$$

$$w_{ip} = \frac{1}{k_L}\ln\left[1 + exp\left(k_L(W - W_L)\right)\right] \tag{6}$$

where, k_N and k_L represent the vertical distance between the intersection points of the two tangents at points N, and L (Figure 1) and the measured shrinkage curve, respectively [$kg_{soil}\ kg_{water}^{-1}$], W_{miN}^{eq} is the micro-pore water content calculated by (equation 2b) but by using W_N instead of W, W_N is the water content at the intersection point (N) in (Figure 1) and represents the water content of the primary peds at a dry state such that $W_N = max(w_{re})$ [$kg_{water}\ kg_{soil}^{-1}$], w_{re} is the water pool associated with the residual shrinkage phase of the shrinkage curve [$kg_{water}\ kg_{soil}^{-1}$], W_L is the water content at the intersection point (L) (Figure 1) such that $W_L = W_M + max(w_{st})$ [$kg_{water}\ kg_{soil}^{-1}$], and W_M is the water content at the intersection point (M) (Figure

1) such that $W_M = W_N + max(w_{bs})$ and it represents the saturated water content of the micropore domain [$\mathrm{kg_{water}\ kg_{soil}^{-1}}$].

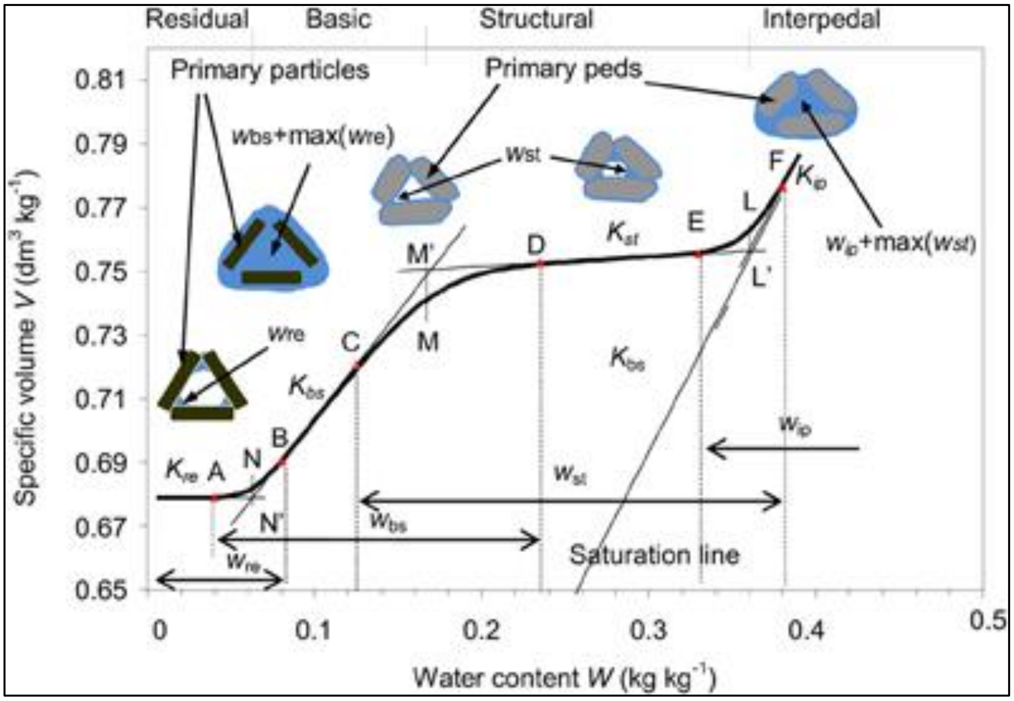

Fig. 1. Shrinkage curve and pedostructure regions illustration (Reprinted from: Erik Braudeau, Assi, Boukcim, & Mohtar, 2014)

Table 1. The state variables and the corresponding parameters of the Pedostructure WRC and ShC (Braudeau et al., 2014)

Symbol	Definition	Unit	Corresponding hydro-structural parameters
W_{Sat}	The pedostructure saturated water content	$\mathrm{kg_{water}\ kg_{soil}^{-1}}$	$W_{maSat}^{eq}, W_{miSat}^{eq}$
W	Pedostructure water content	$\mathrm{kg_{water}\ kg_{soil}^{-1}}$	$\bar{E}/A\ , \bar{E}_{ma}/A$
W_{mi}^{eq}	Micropore water content of the pedostructure	$\mathrm{kg_{water}\ kg_{soil}^{-1}}$	
W_{ma}^{eq}	Macropore water content of the pedostructure	$\mathrm{kg_{water}\ kg_{soil}^{-1}}$	
$h^{eq}(W)$ $h_{mi}\ (W_{mi}^{eq})$ $h_{ma}\ (W_{ma}^{eq})$	Pedostructure water potential which is in instantaneous equilibrium between inside and outside the primary peds, such that: $h_{mi} = h_{ma} = h$	dm ~ kPa	$W_{maSat}^{eq}, W_{miSat}^{eq}$ $\bar{E}_{ma}\ ,\ \bar{E}_{mi}$
$\bar{V}$	The specific volume of the pedostructure	$\mathrm{dm^3\ kg_{soil}^{-1}}$	$\bar{V}_o\ , K_{bs}\ , K_{st}\ , K_{ip}$
w_{re}^{eq}	The specific water content of the water pool associated with the residual linear shrinkage phase of the pedostructure	$\mathrm{kg_{water}\ kg_{soil}^{-1}}$	k_N, W_N
w_{bs}^{eq}	The specific water content of the water pool associated with the basic linear shrinkage phase of the pedostructure	$\mathrm{kg_{water}\ kg_{soil}^{-1}}$	
w_{st}^{eq}	The specific water content of the water pool associated with the structural linear shrinkage phase of the pedostructure	$\mathrm{kg_{water}\ kg_{soil}^{-1}}$	
w_{ip}^{eq}	The specific water content of the water pool associated with the interpedal linear shrinkage phase of the pedostructure, parallel to the saturation line	$\mathrm{kg_{water}\ kg_{soil}^{-1}}$	k_L, W_L

5. RESEARCH DESIGN AND METHODOLOGY

This research is a part of a multi-disciplinary research **“Germination, growth, nutrient composition, yield and economic benefits of collard greens in response to organic amendment types and rates”** conducted by 40 researchers, faculties and students from PVAMU and Texas A&M University.

5.1. Study area

PVAMU Research Farm is located northwest of the Greater Houston Metropolitan Area (Figure 2) with an average annual rainfall (average of 1981–2010) of about1,118 mm yr^{-1} spread over the entire year with over 60% occurring between June and October. The climate is hot during summer when temperatures tend to be in the upper 26 - 32°C range and cooler during winter when temperatures drop to 10 °C range and lower. High temperatures in July average 35°C while temperatures in January average around 3°C. The experimental field of Collard Greens is located at the middle of the University Farm. The soil at the site is classified as a Wockley fine sandy loam (WoA) (Figure 3, Table 2,3 and 4), with 0-1% slope.

Fig. 2. Location of the University Farm, PVAMU and experimental field of Leafy Greens (Google Map[1])

[1] Google. (n.d.). [Google maps view of Leafy Green Farm, Prairie View Texas A&M University]. Retrieved October 1, 2018, from https://goo.gl/maps/pEiRgGMjh2H2

Fig. 3. Major soil types in the University Farm, PVAMU (Soil type in the experimental field: WoA—Wockley fine sandy loam)[1]

[1] Source: Web Soil Survey (https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx)

Table 2. The map units in Fig.3 description[1]

Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
HoB	Hockley loamy fine sand, 1 to 3 percent slopes	162	23.70%
HoC	Hockley fine sandy loam, 3 to 5 percent slopes	32.9	4.80%
KeD	Kenney loamy fine sand, 2 to 8 percent slopes	23.1	3.40%
TaC	Tabor fine sandy loam, 1 to 5 percent slopes	0.4	0.10%
TeC	Tremona loamy fine sand, 1 to 5 percent slopes	0	0.00%
W	Water	5.1	0.70%
Wa	Gessner fine sandy loam, 0 to 1 percent slopes, occasionally ponded	147.3	21.50%
WoA	Wockley fine sandy loam, 0 to 1 percent slopes	314	45.80%
Totals for Area of Interest		684.8	100.00%

Table 3. The Wockley soil unit description[1]

Map Unit Composition	Wockley and similar soils: 90 percent
	Minor components: 10 percent
	Estimates are based on observations, descriptions, and transects of the mapunit
Describing of Wockley Setting	Landform: Flats
	Landform position (three-dimensional): Dip
	Down-slope shape: Linear
	Across-slope shape: Linear
	Parent material: Late pliocene to early pleistocene loamy fluviomarine deposits derived from igneous, metamorphic and sedimentary rock
Typical profile	A - 0 to 7 inches: fine sandy loam
	E - 7 to 22 inches: fine sandy loam
	Btc - 22 to 58 inches: sandy clay loam
	Btcv - 58 to 80 inches: sandy clay loam

[1] Soil Survey Geographic Database (SSURGO), NRCS

Table 4. The Wockley soil unit properties[1]

Map Symbol and soil name		Depth	Sand	Silt	Clay	Moist Bulk Density	Saturated hydraulic conductivity	Available water capacity	Linear Extensi-bility	Organic Matter	Erosion factors			Wind Erodi-bility Group	Wind Erodi-bility Index
		In	Pct	Pct	Pct	g/cc	micro m/sec	In/In	Pct	Pct	Kw	Kf	T		
WoA:	Wockley	0-7	61-70	26-32	7-Apr	1.48-1.72	1.40-4.00	0.11-0.15	0.3-0.5	0.8-2.0	0.4	0.4	5	3	86
		22-Jul	51-62	29-40	9-Jun	1.62-1.75	1.40-4.00	0.11-0.15	0.3-0.6	0.2-0.6	0.4	0.4			
		22-58	45-52	17-31	22-37	1.57-1.67	1.40-4.00	0.11-0.17	0.8-2.5	0.2-0.4	0.3	0.3			
		58-80	38-46	19-23	31-46	1.55-1.78	1.40-4.00	0.11-0.17	1.7-3.0	0.1-0.2	0.3	0.3			

5.2.Experimental design

36 plots were selected to plant Collard Green on PVAMU research farm. Three types of organic amendments: Chicken manure, Dairy Manure and Milorganite were applied to the plots on three application rates (non-amendment control (0 kgN/ha), half recommended rate (168 kgN/ha), recommended rate (336 kgN/ha) and double of the recommended rate (672 kgN/ha). Size of plots are 10 ft. x 5 ft. The farm planted with collard green inside the plots area in October 2017 (Figure 4 and Table 5).

[1] Soil Survey Geographic Database (SSURGO), NRCS

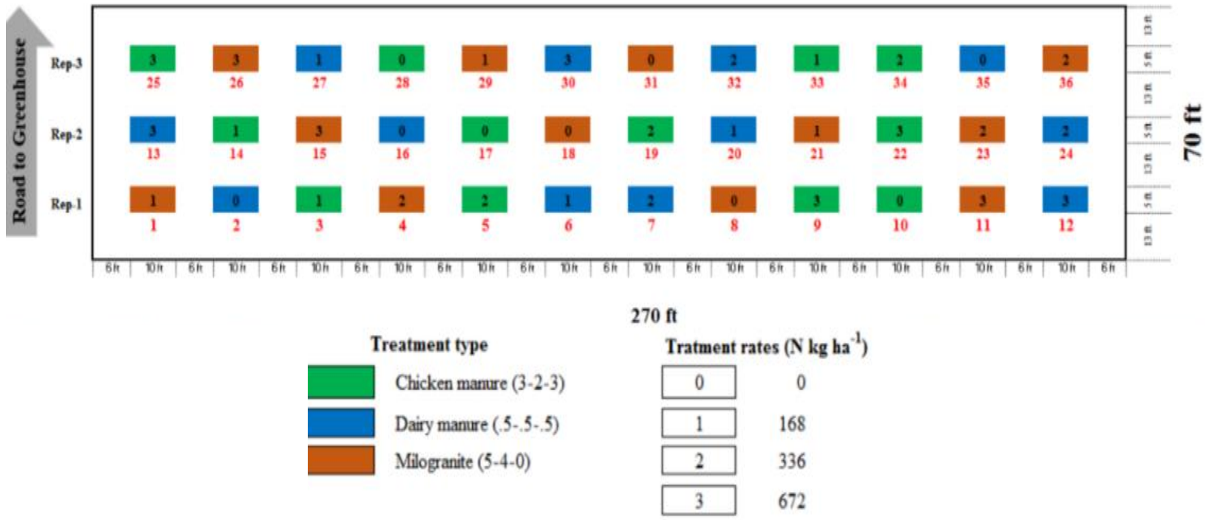

Fig. 4. Experiment Plots Information Map of PVAMU Collard Green Farm (Reprint from the Project Brochure) [1]

[1] Reprint from the Project Brochure: Prairie View University. (2018). Germination, Growth, Nutrient Composition, Yield, and Economic Benefits of Collard Greens in Response to Organic Amendment Types and Rates, Cooperative Agricultural Research Center, College of Agriculture and Human Sciences, Prairie View A&M University. Prairie View, Tx

Table 5. Soil samples Information

Horizon	Treatment	Application Rate (N.Kg.ha $^{-1}$)	Code	Plots
A	Control	0	0	2,8,10,16,17,18,28,31,35
	Chicken Manure	168	A_Ch_1	3,14,33
		336	A_Ch_2	5,19,34
		672	A_Ch_3	9,22,25
	Dairy Manure	168	A_D_1	6,20,27
		336	A_D_2	7,24,32
		672	A_D_3	12,13,30
	Milorganite	168	A_M_1	1,21,29
		336	A_M_2	4,23,36
		672	A_M_3	11,15,26
B	Control	0	0	2,8,10,16,17,18,28,31,35
	Chicken Manure	168	B_Ch_1	3,14,33
		336	B_Ch_2	5,19,34
		672	B_Ch_3	9,22,25
	Dairy Manure	168	B_D_1	6,20,27
		336	B_D_2	7,24,32
		672	B_D_3	12,13,30
	Milorganite	168	B_M_1	1,21,29
		336	B_M_2	4,23,36
		672	B_M_3	11,15,26

5.3. Sampling

Thirty-six undistributed standard soil core samples ((r=5cm, h= 5cm) ~ 100 cm^3) were collected from "A horizon" (0-15 cm depth) and 36 more from "B Horizon" (30 cm) and sent to Pedostructure Characterization Laboratory at Texas A&M University for the hydro-structural characterization.

5.4. Laboratory measurement

The pedostructure concept was used in analyzing the dynamic in soil hydro-structural properties. Figure 5 represents the pedostructure state variables and parameters. To the left is a standard undisturbed soil core ((r=5cm, h= 5cm) ~ 100 cm3)) representing the pedostructure (soil natural aggregates organization) of the soil horizon. To the right, the characteristic parameters of the two water pools of this aggregates structure, micro- and macro-pore domains. Using these water pools and their content changes at various water potentials, fundamental relationships were developed and applied to predict water flow.

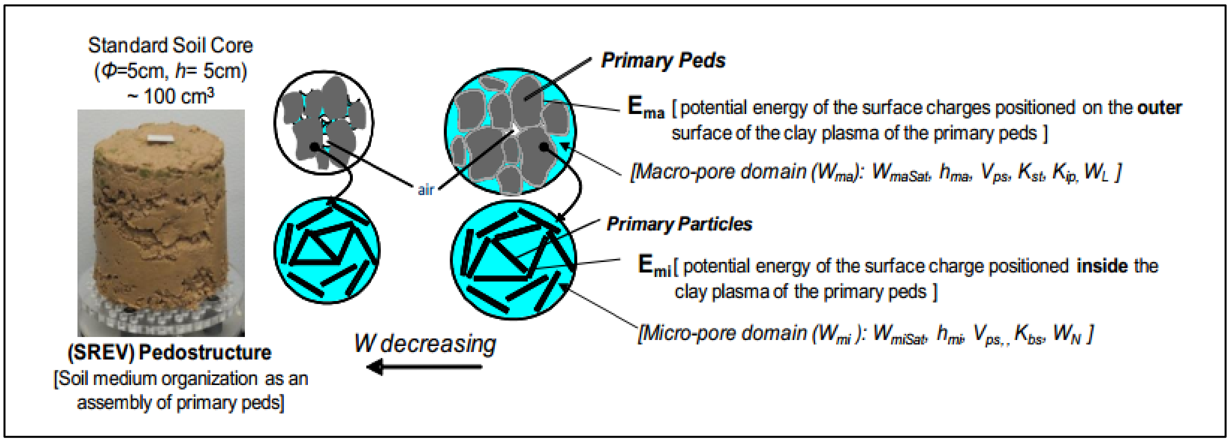

Fig. 5. Standard soil core and aggregate subparts with their hydrostructural parameters (reprinted from Braudeau et al., 2016)

TypoSoil™ is a device (Figure 6) used to measure, continuously and simultaneously, six values (weight "by a balance", soil suction "by ceramic cup tensiometer, and soil cylinder diameter "by two laser beams", and soil cylinder height "by a laser spot") for eight unconfined cylindrical soil cores (100 cm3). The measurement will then be used to construct the two-soil moisture characteristic curves: a water retention curve (WRC) and soil shrinkage curve (ShC).

To construct the WRC and the ShC, the soil water content and the soil specific volume need to be calculated from the measured state variables, such that:

$$W = \frac{(m - M_s)}{M_s} \tag{7}$$

where W is the water content of the soil sample [$\mathrm{Kg_{water}\ kg_{solid}^{-1}}$], m is the measured mass of the soil sample [$\mathrm{kg_{water}}$], M_s is the dry mass of the soil sample at 105 °C [$\mathrm{kg_{solid}}$].

$$\bar{V} = \frac{\pi D^2 H}{4 M_s} \times 10^{-4} \quad (8)$$

where, $\bar{V}$ is the specific volume of the soil sample [dm^3 $\mathrm{Kg_{solid}^{-1}}$], $D\ and\ H$ are, respectively, the measured diameter and height of the soil sample by the laser sensors [dm], M_s is the dry mass of the soil sample at 105 °C [$\mathrm{kg_{solid}}$].

Then, the water retention curve (WRC) is constructed by drawing the calculated soil water content (W [$\mathrm{Kg_{water}\ kg_{solid}^{-1}}$]) vs. the measured soil suction (h [dm ~ kPa]). And, the soil shrinkage curve (ShC) is constructed by drawing the calculated soil water content (W [$\mathrm{Kg_{water}\ kg_{solid}^{-1}}$]) vs. the calculated specific volume $\bar{V}$ [dm^3 $\mathrm{Kg_{solid}^{-1}}$].

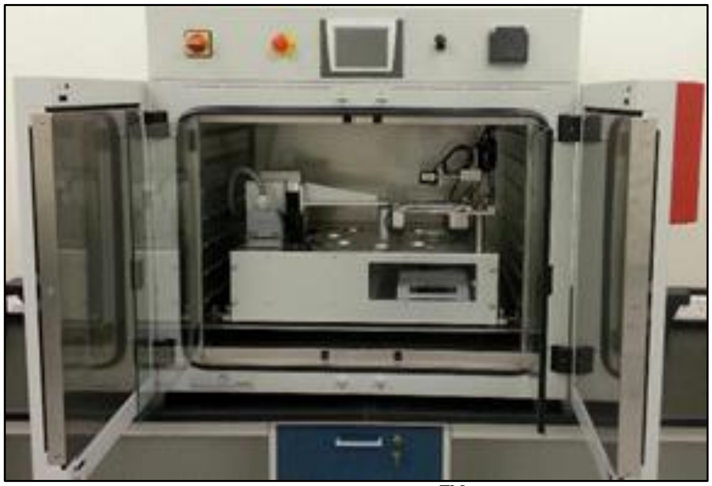

Fig. 6. TypoSoil^{TM}

The hydro-structural parameters of the pedostructure will be extracted by adjusting the thermodynamic equations of WRC and ShC to the measured ones by TypoSoil^{TM} as outlined in Assi et al., (2014). Then, the parameters will be used to develop the pedostructure water contents curves: micro, macro, and residual water contents curves to extract the values of permeant wilting point and field capacity based on the work of Assi et al., (2018).

Both the hydro-structural parameters and the soil-water holding properties will be used to identify a soil quality index.

5.5. Data analysis

5.5.1. Extracting parameters

After constructing the WRCs and ShCs for the 72 soil samples as explained in section 6.4, the hydro-structural parameters for each soil sample were obtained following the methodology outlined in Assi et al. (2014) and Braudeau et al., (2016). The hydro-structural characterization spreadsheets available online at https://wefnexus.tamu.edu/hydro-structural-pedology/ were used in analyzing the soil samples. The extraction of the hydro-structural parameters was done by adjusting the measured WRCs and ShCs to the theoretical and thermodynamic equations (1-6).

5.5.2. Calculating available water

The calculation of the available water capacity was conducted following the procedures outlined in Assi et al. (2018). Available water capacity is the difference between the field capacity (FC) and permeant wilting point (PWP).

Field capacity (FC): the water content at field capacity resembles the water content at which the thermodynamic energies between soil and water are much greater than the gravitational energies. Based on the thermodynamic perception of pedostructure, as described before, this water content can then be recognised by the fast shift in the micro-pore water content curve. Therefore, FC of a soil happens at the maximum of the change in incline of the W_{mi} curve. This value can be distinguished by determining the root of the third derivative of W_{mi} curve, or by numerical solutions. At this point, all the interpedal water will have disappeared.

Permanent Wilting Point (PWP): the water content at PWP resembles the water content at the air entrance point of micro-pore region. At this point, a capillary break inside the micro-porosity of primary peds happens and the water cannot be touched by the plant roots at the contact surface of the peds. This water content matches to point B in Figure 1. At this point, the soil suction is about 3791 hPa. So, Point B can describe the greatest changes in the slope of the residual water content curve w_{re} (W), as shown in Figure 1, the soil water content at this maximum change in slope will be used as the permanent wilting point (Assi et al. 2018).

Available Water Capacity (AW): available water capacity can be then identified as the difference between the FC and PWP, such that:

$$AW = FC - PWP \tag{9}$$

5.5.3. Statistical analysis

5.5.3.1. Correlation analysis

Data extracted from the optimization process includes 12 hydro-structural parameters that along with their definitions and units are listed below in Table 6. Hydro-structural parameters defined after model optimization. All these parameters were identified for each plot of the 36 plots shown in Figure 4 and as well for each soil horizon (A and B). So, in total there were 72 soil cores.

Table 6. Hydro-structural parameters defined after model optimization

Parameter	Unit	Description
W_{sat}	Kg_{water}/Kg_{soil}	Saturated Water Content
W_{miSat}	Kg_{water}/Kg_{soil}	Micropore Volume Water Content at Saturation
W_{maSat}	Kg_{water}/Kg_{soil}	Macropore Volume Water Content at Saturation
W_L	Kg_{water}/Kg_{soil}	Water Content at the poin that all interpedal water has drained
AW	Kg_{water}/Kg_{soil}	Available Water
E_{mi}	$J/Kg_{\ solids}$	Potential energy of the surface charges of the clay particles inside of the primary peds
E_{ma}	$J/Kg_{\ solids}$	Potential energy of the surface charges of the clay particles outside of the primary peds
K_{bs}	$dm^3/Kg_{\ water}$	Slope of the basic shrinkage phase of SSC
K_{st}	$dm^3/Kg_{\ water}$	Slope of the structure shrinkage phase of SSC
K_{ip}	$dm^3/Kg_{\ water}$	Slope of interpedal shrinkage phase of the SSC
V_0	$dm^3/Kg_{\ soil}$	Shrinkage limit Specific Volume
ΔShC	$dm^3/Kg_{\ soil}$	Shrinkage Amplitude

Since a soil quality index should be a combination of a small number of variables as much as it's possible, it is necessary to select the most representative and appropriate set of variables. This task can proceed by correlation coefficient analysis. Correlation coefficients between parameters tell us how strongly two variables are related to each other. By considering some more representative parameters and putting aside others which are highly correlated to selected parameters, we can minimize the possible soil quality index combination and also avoid unnecessary calculation and complexity.

5.5.3.2. Location dependency analysis

In this experiment, 3 plots of the same treatment and the same application rate were randomly located on the farm (for example, in Figure 4, 5A, 19A, 34A represent the chicken manure treatment at336 KgN/ha application rate). To consider these 3 plots as 3 replications that represent the same situation (treatment and rate), data driven from these 3 plots should not be significantly different. This fact will allow us to use them as counterparts or replicates of one examined case. If they are significantly different in measured parameters it means that there are variables related to location of samples which we didn't considered in calculations. An examples could be change in the texture of soil throughout the farm.

Therefore, since there are 9 control samples all around the farm and by examining data of these 9 plots regarding the location dependency, the accuracy of the information obtained from the experiment can be certified or rejected for all samples based on the significance of differences between values of parameters. The statistical assumption here will be that variances around the mean are all caused by random errors. Thus, a statistical normality test Kolmogorov-Smirnov has been done for all parameters of these 9 samples to check the location independence in acceptable confidence levels.

5.5.3.3.Statistical significance

After assuring the accuracy of measured data, it’s time to detect hydro-structural source of variation in data. Regarding the research question, two sets of comparison have been done between plots:

1- Comparison of samples with the same treatment type but different application rate.
2- Comparison of samples with the same application rate but different treatments.

Analysis of Variance (ANOVA) statistical method with 95% level of confidence has been used to reveal meaningful differences between the extracted hydro-structural parameters. The null hypothesis for ANOVA is that the mean (average value of the dependent variable) is the same for all groups. The alternative or research hypothesis is that the average is not the same for all groups (at least one group is different from others significantly) and changes in treatment type or rate caused this significant change. The ANOVA test procedure produces an F-statistic, which is used to calculate the p-value. An important assumption underlies the Analysis of Variance is that all treatments have similar variance. If there are strong reasons to doubt this then the data might need to be transformed before the test can be done. Thus, first, homogeneity of variances should be investigated in each group of comparisons. Folded form F-test was used here to inspect homogeneity of variances. This method basically uses the ratio of the larger sample variance to the smaller sample variance to test its null hypothesis which is all variances are equal.

6. RESULTS

In this section, the measured soil shrinkage and soil-water retention curves, along with any significant differences due to the change of treatment type or the application rate of treatments, will be discussed. Each pedostructure parameter will then be analyzed to determine what differences, if any, occur in the parameter due to the changes in either the treatment type or the application rate, or both. Finally, the ability to develop a soil quality indicator based on hydro-structural parameters will be discussed.

First optimizing the dataset size should be examined. By looking at correlation coefficients in Table 7 between parameters in both horizons (average of 3 assumed replications calculated), apparently, there are no strong correlations which could lead to use fewer parameters. Generally, most of the parameters are insignificantly or negatively correlated with each other. There are few parameters in A Horizon with correlation coefficients of more than 80% but because such level of correlations did not exist for the same parameters in B horizon, classification is not an option.

Table 7. Correlation Coefficient between Hydro-structural Parameters of samples from A & B-Horizon

	W_{sat}		W_{miSat}		W_{maSat}		E_{mi}		W_L		E_{ma}		K_{bs}		K_{st}		K_{ip}		V_0		ΔShC	
Horizon	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
W_{sat}																						
W_{miSat}	0.388	0.426																				
W_{maSat}	-0.255	0.261	-0.990	-0.762																		
E_{mi}	0.503	-0.242	0.965	-0.160	-0.936	-0.003																
W_L	0.844	0.743	0.212	0.249	-0.094	0.266	0.266	-0.416														
E_{ma}	-0.120	-0.148	-0.833	-0.724	0.855	0.667	-0.760	-0.182	-0.032	0.102												
K_{bs}	0.514	-0.142	-0.107	0.225	0.190	-0.342	-0.034	0.030	0.681	-0.450	0.126	-0.274										
K_{st}	-0.319	0.316	0.366	0.447	-0.432	-0.251	0.293	-0.285	-0.311	0.355	-0.380	-0.400	-0.506	-0.379								
K_{ip}	0.034	-0.014	0.537	-0.430	-0.558	0.449	0.507	-0.302	0.110	-0.189	-0.280	0.600	-0.239	0.467	0.177	-0.533						
V_0	0.725	0.611	0.710	0.495	-0.635	-0.091	0.747	-0.404	0.560	0.720	-0.293	-0.161	0.176	0.138	0.107	0.116	0.410	0.041				
ΔShC	0.070	0.596	0.587	0.326	-0.605	0.079	0.504	-0.298	-0.071	0.163	-0.589	-0.183	-0.013	0.594	0.201	-0.051	0.223	0.497	0.460	0.445		
AW	0.454	0.220	0.952	0.626	-0.930	-0.511	0.926	-0.374	0.291	0.114	-0.778	-0.348	-0.035	0.118	0.218	0.176	0.439	-0.117	0.707	0.440	0.440	0.089

Next essential step is detecting location dependency of parameters of 9 control samples from A and B horizons. Results are shown in Figure 7. The statistical null hypothesis is that all variations from the average are because of random errors and data of these 9 samples can be considered following a normal distribution. Two level of confidence, 95% and 99% examined for detecting parameters that show dependency to the location. And the reason is that in different locations, there might be different textures or structures which cause heterogeneity and make any interpretation from data difficult. Based on results, parameters do not show any significant changes mostly by the 95% level and few of them by the 99% confidence level.

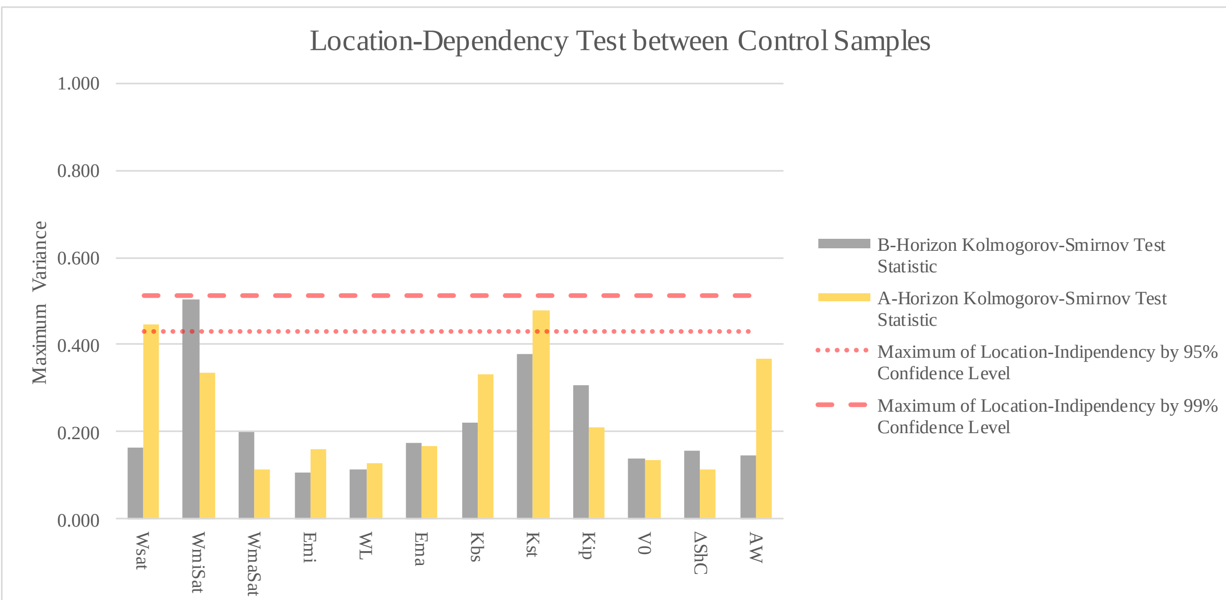

Fig. 7. Location Dependency test for A and B-Horizon 9 control samples

By ensuring location independence, we can consider every 3 samples with the same treatment and rate as replications. Thus, for every 12 cases, it can be assumed that there are 3 replications (Table A.1 to Table A-6).

6.1. Same treatment and different application rate

In this type of comparison, representative parameters of samples with the same treatment but different application rates were evaluated. Tables A-1 to A-6 in the appendix display values of parameters for each case. In this comparison, the goal is to know if changing the application rate caused meaningful changes in the soil hydro-structural parameters or not.

6.1.1. Homogeneity of variance test

Folded form F-test has been done for parameters in this type of comparison. Fig. 8, Fig. 9, Fig. 10 show the results of the homogeneity test. This test is critical before doing variance analysis. If variances from 4 groups (0, 1, 2, 3) don't reveal homogeneity in an acceptable level of confidence, it means variations around the average for each set of replications do not have same error source and practically these groups statistics cannot be compared to each other. A possible solution is the transformation of data such as logarithmic transformation which match values' variances up because it scales down large variations exponentially. Here logarithmic transformation has been done for some of the parameters to push the F-statistics below the maximum possible value[2]. As mentioned before, this test statistic is the result of dividing maximum variance by minimum variance between groups. There are few cases that the statistics were the result of dividing to 0 and they replaced by 200. The reason is that some groups have three same values and this fact causes zero variance. This is the drawback of a small size of replications that makes it possible here to have three exact same values. These cases' passing the

[2] A_Emi, A_Kst, A_Aw, B_Ema in the chicken manure group A_WmiSat, A_Emi, A_Kst in the dairy manure group and A_WmaSat, A_Emi, A_Kst in the milorganite group

limit were ignored since variances were all near to zero and close enough but the statistics weren't able to show this fact[3]. At the end, all parameters and their transferred displayed homogeneity and qualified to variance analysis.

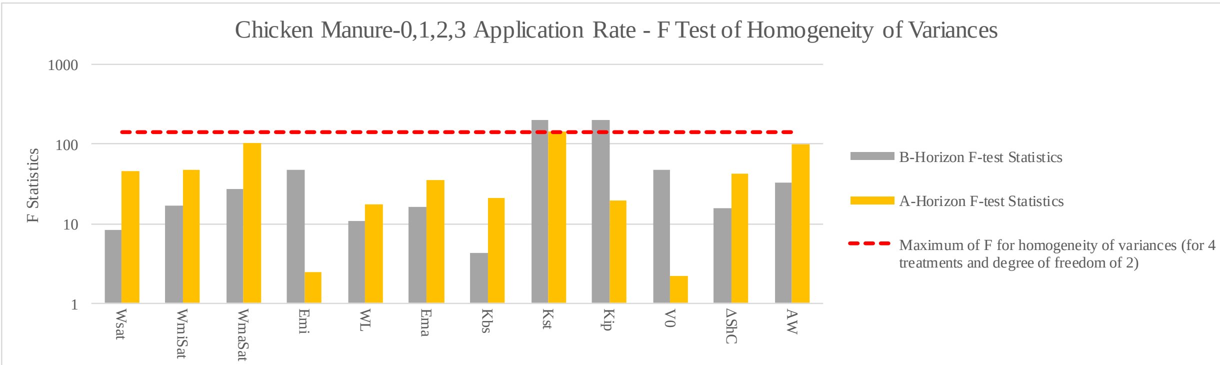

Fig. 8. Test of homogeneity for samples from plots with chicken manure and 3 rates of application

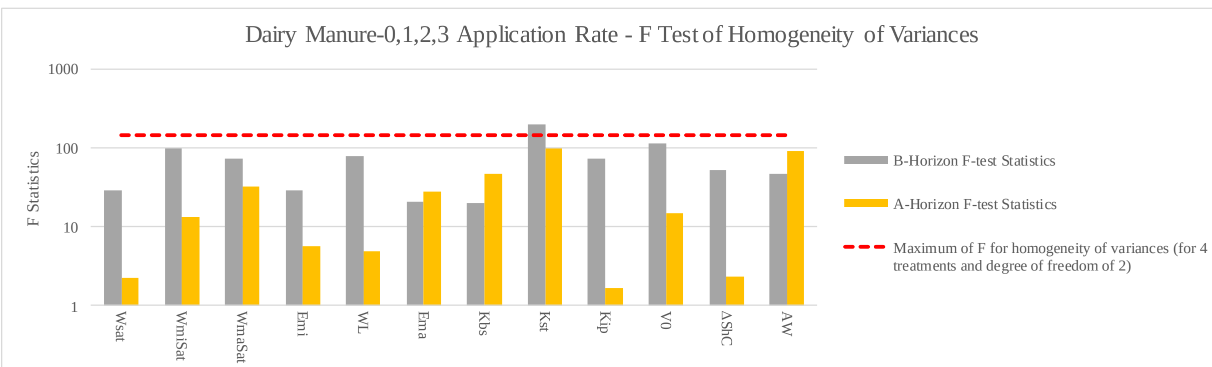

Fig. 9. Test of homogeneity for samples from plots with dairy manure and 3 rates of application

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[3] A_Kst, B_Kip in the chicken manure group, B_Kst in the dairy manure group, A_Kip in the milorganite group

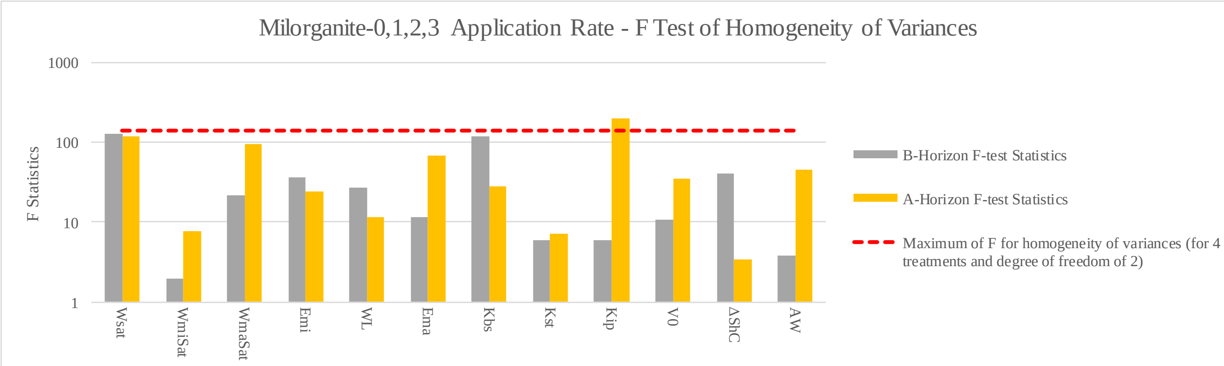

Fig. 10. Test of homogeneity for samples from plots with milorganite and 3 rates of application

6.1.2. Significance analysis

Fig. 11, Fig. 12 and Fig. 13 show results of Analysis of Variance test which is for detecting significant differences in parameters values here because of changing the application rate. The red line shows the minimum value of the calculated F in 95% confidence level (that statistically is for 4 treatment and 2 degree of freedom. Control sets accounted for one type of treatment). Parameters for A and B horizon can be seen beside each other. Parameters that cross the line imply the fact that the parameter of at least one set has changed significantly by the 95% level of confidence. Type I and II errors illuminate how much we can trust in accepting or rejecting the statistical null hypothesis. If a parameter has not passed the red line it can be implied that there is no significant difference between values in the group. So, the error percentage beside bars shows the probability of rejecting a true hypothesis (type I error). The same way for bars that have passed the red line, the null hypothesis has been accepted and there is a significant difference between sets and the error percentage explains the probability of accepting a false hypothesis (error type II).

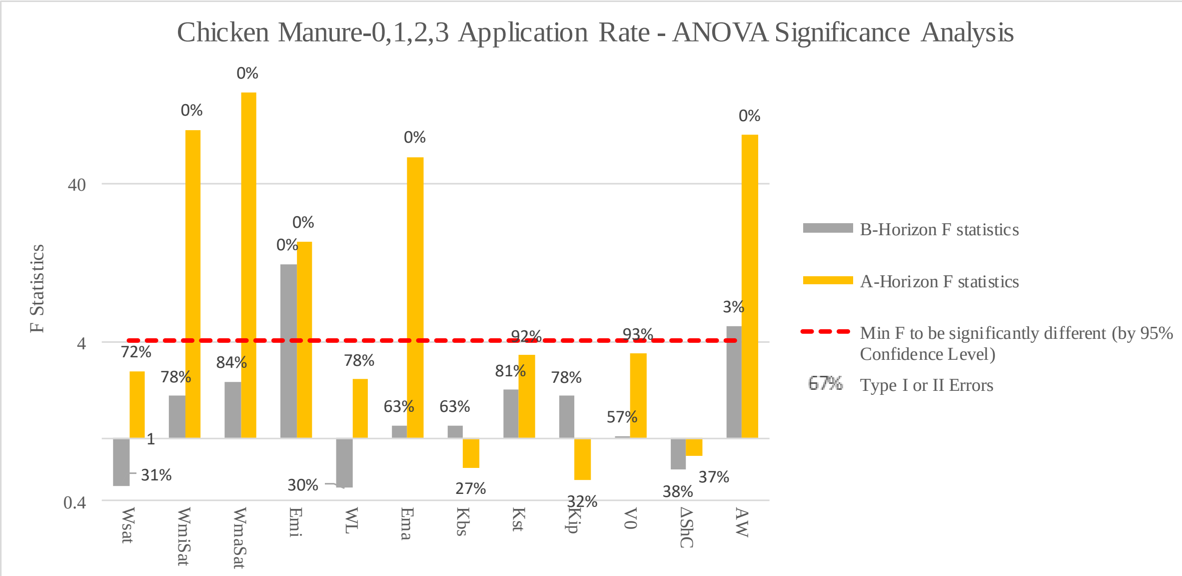

Fig. 11. Four sets of samples with chicken manure treatment by different application rates comparison – The red dashed line shows the minimum of F statistics to be significantly different. Parameters that crossed the line imply the fact that the parameter of at least one set has changed significantly by the 95% level of confidence.

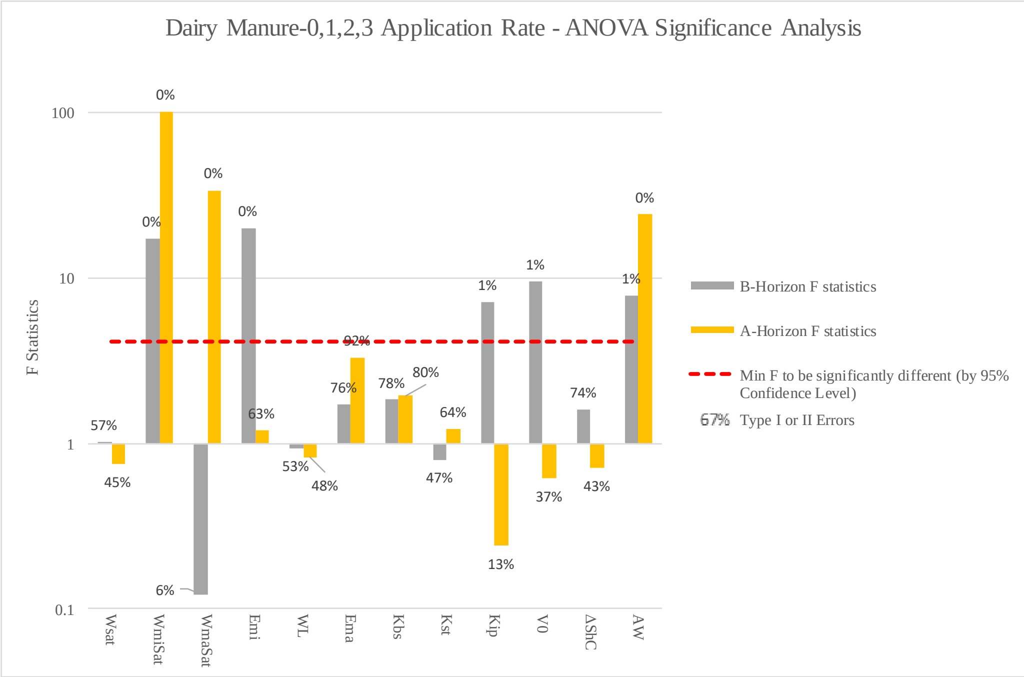

Fig. 12. Four sets of samples with dairy manure treatment by different application rates comparison – The red dashed line shows the minimum of F statistics to be significantly different. Parameters that crossed the line imply the fact that the parameter of at least one set has changed significantly by 95% level of confidence.

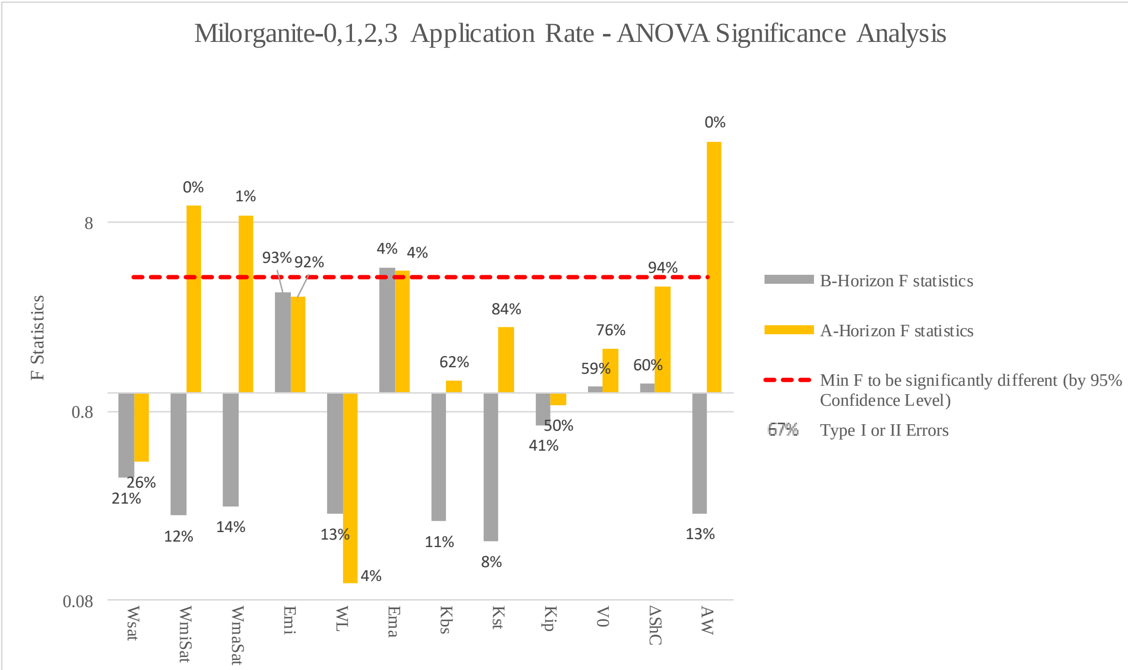

Fig. 13. Four sets of samples with milorganite treatment by different application rates comparison – The red dashed line shows the minimum of F statistics to be significantly different. Parameters that crossed the line imply the fact that the parameter of at least one set has changed significantly by 95% level of confidence.

Finishing statistics evaluation, there can be three set of parameters. Group of unchanged, group of changed and the moderately unchanged group which are statistically unchanged but because of error type I for more than 80%, there is a high possibility of being changed. This classification does not mean that the non-significant differences will be ignored, rather it will help to interpret possibilities that were close to happening.

6.1.3. Parametric evaluation

The measured soil shrinkage curves and water retention curves for each treatment type with different rates at different horizon can be seen in Fig.14, Fig. 15 and Fig.16. The average of hydro-structural parameters can also be found in table A.7 in the appendix. Distinct water pools that can be easily seen in Fig. 1 is not discernable from these curves indicating the law shrinkage ability of these soils. However, some qualitative results can be discerned. Putting these qualitative results beside quantitative probabilities that have been calculated for each parameter in the previous section can give a rational explanation about each scenario. In this type of comparison, interpretations are only focused on changes in the rate and the objective is not to compare different treatments effects. This is the area of discussion for the next session that different treatment with the same rate will be compared.

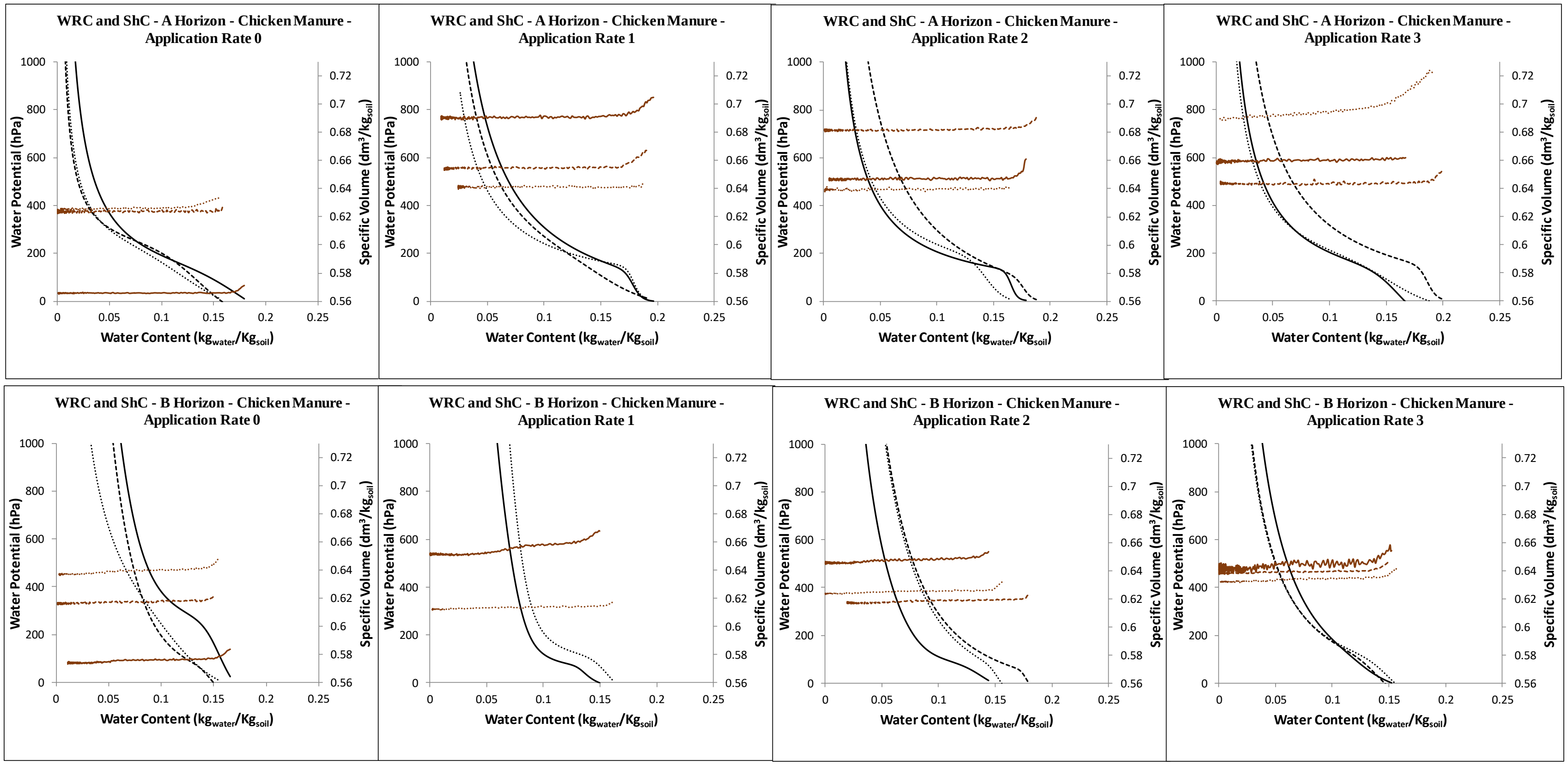

Fig. 14. Representative shrinkage curves (maroon) and soil water retention curves (black) for horizon A (top row) and B (down row) samples from chicken manure treatment in different application rates

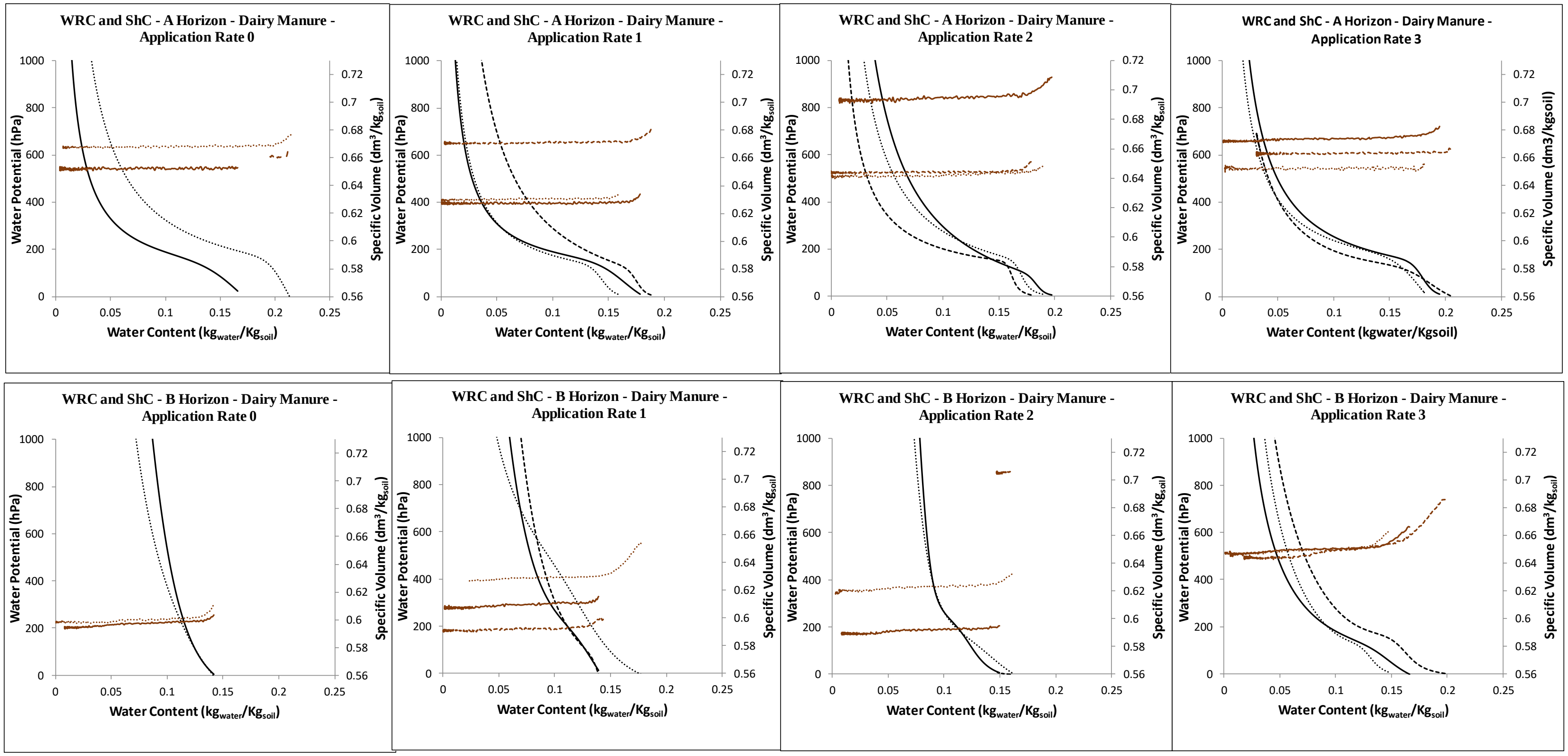

Fig. 15. Representative shrinkage curves (maroon) and soil water retention curves (black) for horizon A (top row) and B (down row) samples from dairy manure treatment in different application rates

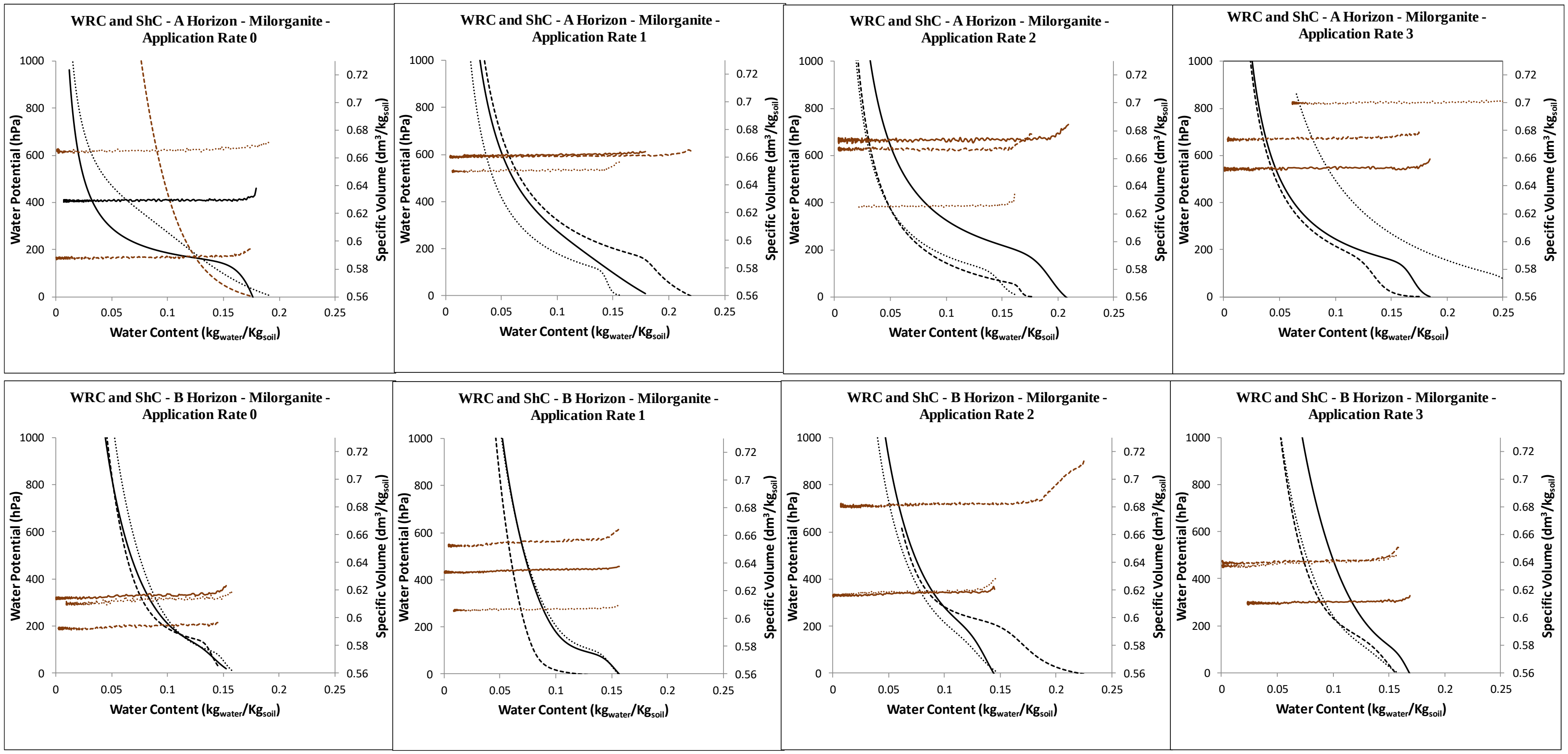

Fig. 16. Representative shrinkage curves (maroon) and soil water retention curves (black) for horizon A (top) and B (down) samples from milorganite treatment in different application rates

6.1.3.1. Soil shrinkage curves

In all 3 treatment application in the A and B-horizon, by increasing the rate of application, specific volume throughout the entire shrinkage curve slightly tends to increase. Although variation in the range 0.1 cannot be strongly significant, it's acceptable to say that the average value of the starting point of ShC curves increased. If we assume that the amount or volume of mesopores and micropores have increased because of raise in the application rate, it means organic matters in treatments helped the improvement of soil structure. This trend is more significant in B-horizon not because of the magnitude of changes, but because of the fact that based on samples observations, B-horizon level is highly compacted and the increase in specific volume shows the effectiveness of using treatments to enhance the soil aggregate structure by biological causes. It means if the only layer that has changed was A-horizon, physical drivers such as air and water movement would enhance the structural changes. But having the rising trend of specific volume even in B-horizon puts no doubt about biological enhancement because of increasing the rate of application. This observation is only based on the graphs interpretation its accuracy depends on compatibility with parametric evaluation.

6.1.3.2.Variation in characteristic parameters of the soil aggregates structure

K_{bs} measures the slope of the shrinkage line as the basic water pool dries (Fig. 1). This parameter represents the volume change with the respect to the water content in the primary peds of the pedostructure. This parameter represents the amount of shrinkage occurring in the soil–water system as the shrinking micropore water is removed from the system. Tables A-1 to A-6 show the values of all parameters for all samples tested, with the means listed in table A.7. Looking at its significance analysis and its values comparing rates in each treatment (Fig. 17), the changes are not significant and there is no trend detected between values even in a small range for both horizons. This fact tells there would not be detectable changes in soil aggregate structure by using different rates of treatments. K_{st}, ΔShC and V_0 are other soil shrinkage curve characteristic parameters that directly related to aggregate structural characteristics and these parameters also do not show significant differences.

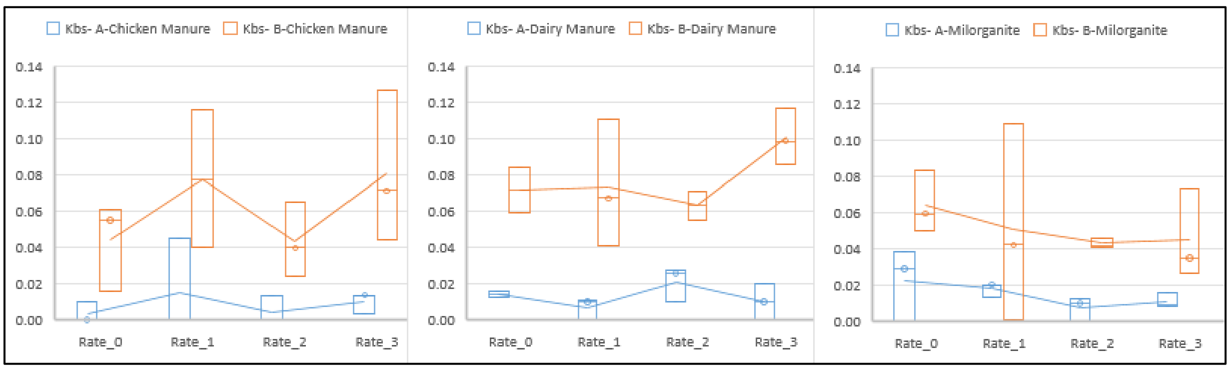

Fig. 17. K_{bt} changes in 3 treatments at different rates

6.1.3.3. **Water retention curve**

In low shrinkage soils, the shrinkage curve is not pronounced enough to indicate pedostructure parameters in the macropore region. By pedostructure methodology used in this research, the soil's continuously measured water retention curve to obtain additional information about the macropore region of soil–water. Results can be seen in Fig.14, Fig. 15 and Fig.16 as before, in black lines.

6.1.3.4. Variation in characteristic parameters of the soil water holding properties

W_L is the water content at the point that all interpedal water has drained. Therefore it's a combination of macro, micropore water content and residual water. Looking at its variation in fig.18 and its statistics reveal that there are no significant changes by using treatments or by increasing the application rate of them in both horizons.

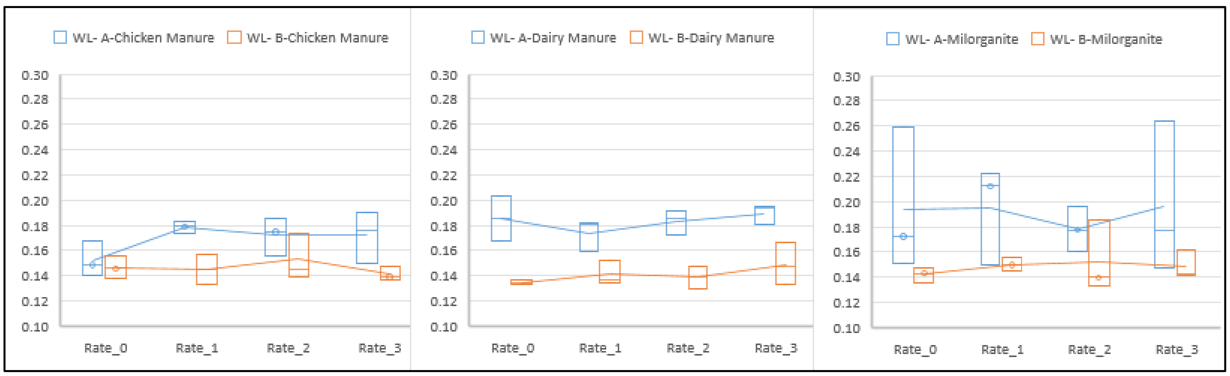

Fig. 18. W_L changes in 3 treatments at different rates

Macropore water content is the water sticks on the external surface of primary peds. Its statistics for this type of comparison shows significant differences for A-Horizon but no significance for B-Horizon. Fig. 19 clearly shows this fact. Although there was no special trend observed for increasing the rate of applications, using treatments themselves caused a significant decrease in macropore water content.

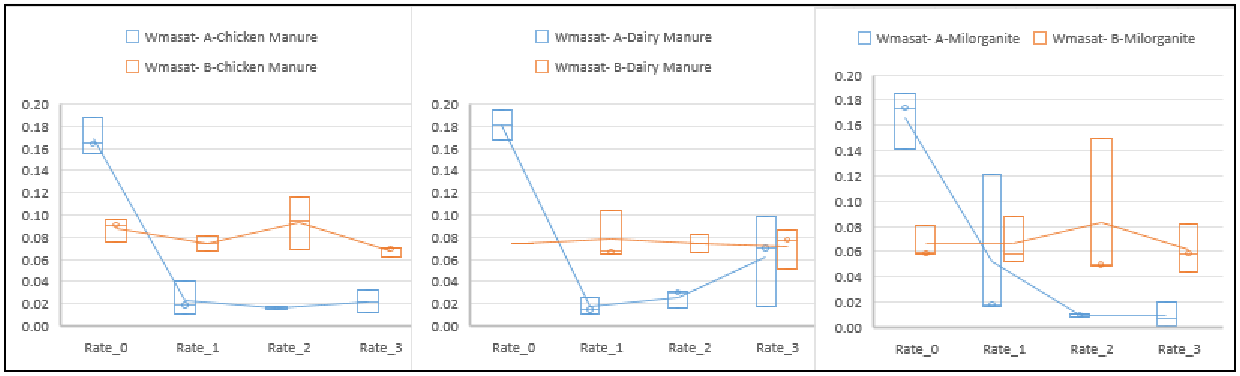

Fig. 19. Macropore volume water content at saturation changes in 3 treatments with different rates

Therefore, adding treatments caused a decrease in this type of water. The reason could be that more organic matter is added and thus more water can be retained in the micro-pore domain, leaving less water available in the macropore domain. One should keep in mind that the overall water content (saturated water content) didn't show significant differences between the horizons and applications rate.

The potential energy on the external surface of the primary peds, highly correlated to macropore water content, is labelled as E_{ma}. It is a measure of the specific energy (in $J.kg^{-1}$soil) needed to remove the water from the macropore domain. The range of values in both horizons is 0.01 to 2.1 which is extremely low (Fig. 20).

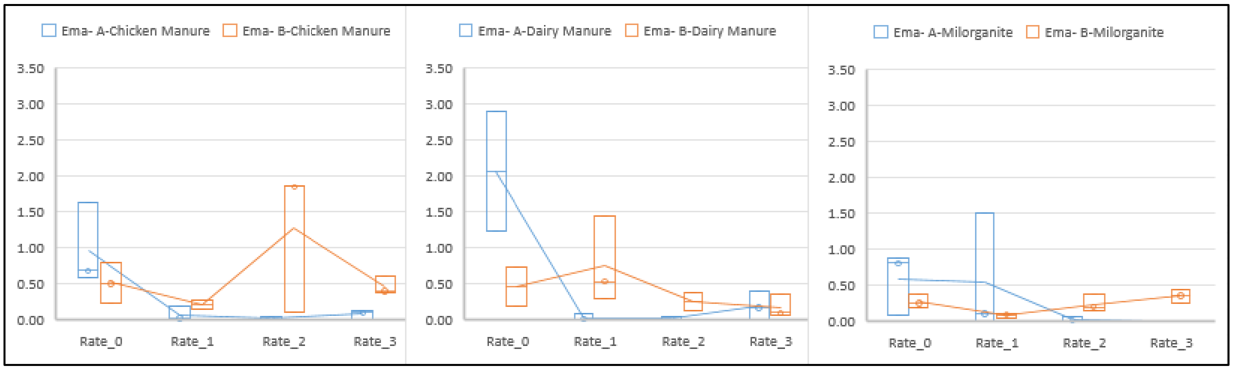

Fig. 20. E_{ma} *changes in 3 treatments at different rates*

However, having its low range in mind, it's necessary to mention that the differences between different application rates are significant for all treatments in A horizon (except for dairy manure but with 92% error type I). Looking at averages and replicates values make it clear that there is a decrease in E_{ma} after using soil treatments (fig. 18). Finally, regarding the changes due to the increase in treatment rate, the total values ranges plus little changes are all mostly insignificant for E_{ma}.

In the micropore part (w_{mi}) (fig. 21), water content has a total reverse story. Adding treatment cause a significant increase in micropore water content only in A-horizon samples. This increase is because of potential energies of the surface charges of organic matter that enhanced the structure of the soil in a way that more water has been retained in micropore spaces. Again, nothing is significant in the case of B-horizon or increasing the application rate in both horizons except for milorganite case that increasing the application rate seems that caused a slight increase in micropore water content.

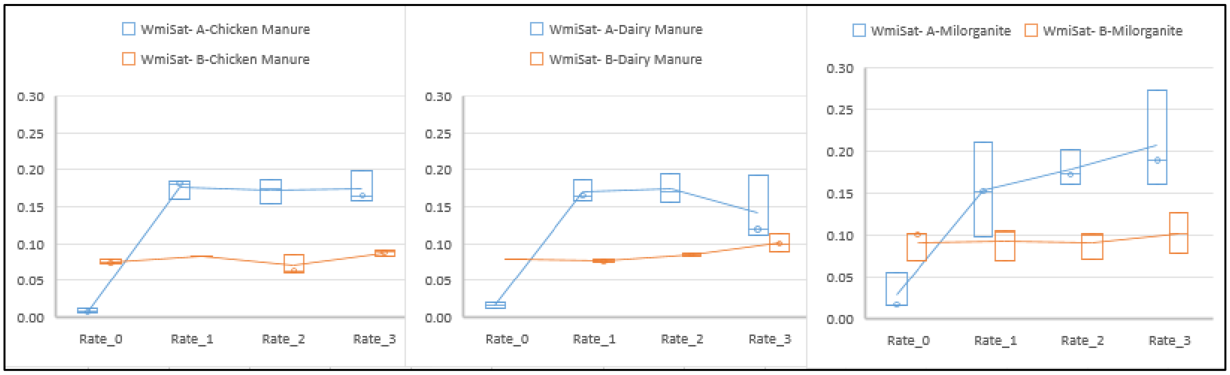

Fig. 21. Micropore domain water content at saturation changes in 3 treatments with different rates

Emi which is the potential energy of the surface charges of the clay particles inside of the primary peds shows significantly and moderately changed in horizon B of all treatments (milorganite statistic is 93%) and for A-horizon except for dairy manure. Let's look at its variation in Fig. 22. Since E_{mi} is correlated to $W_{mi,}$ the expected increase can be seen in A horizon. Emi represents the energy needed to remove the water from the micro-pore domain. In the B horizon of dairy manure treatment E_{mi} shows a significant increase in rate_2 which needs more research or samples to get an accurate conclusion. Since 3 replicate is not that enough to say that the best rate for dairy manure is rate_2. Anyhow, no systematic trend can be interpreted.

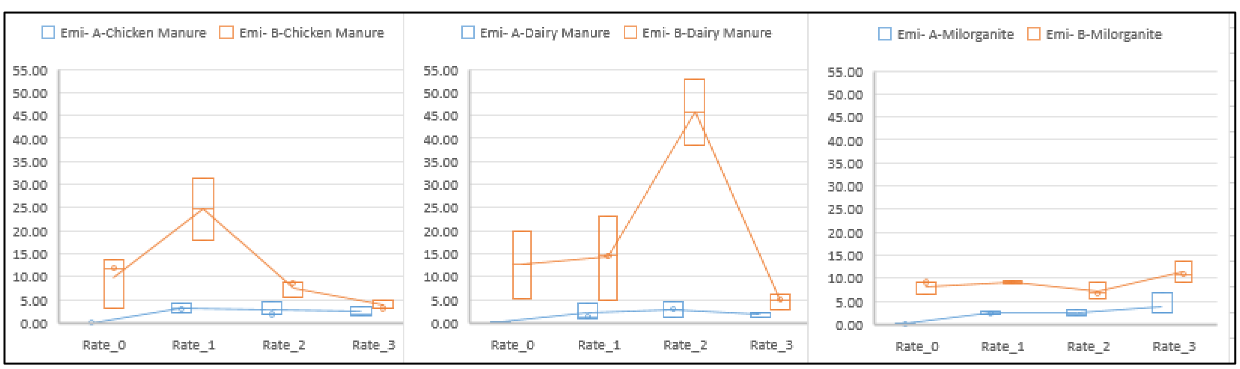

Fig. 22. E_{mi} changes in 3 treatments at different rates

The other parameter related to soil water holding properties is AW which is available water to the plant's root. As described before, AW is the difference between field capacity and permanent wilting point. AW parameter is highly correlated theoretically to W_{miSat} which is the indicator of field capacity. Looking at AW statistics and fig. 23, AW has statistically significant differences between control samples and samples with treatments in different application rates in all treatments and horizons (except for B-horizon in milorganite). **This significance seems to be because of the treatment type rather than the application rate**. However, there might be a reasonable trend of increase in available water by increasing the application rate for dairy manure.

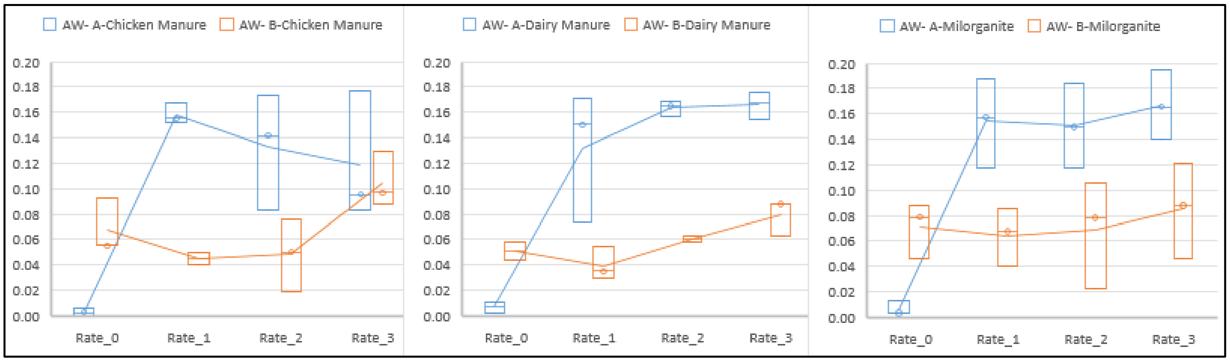

Fig. 23. AW changes in 3 treatments after different rates

6.2. Same application rate and different treatment

In this type of samples comparison, 12 representative parameters with the same application rate and different treatments were evaluated. Therefore, first Ch_1, D_1 and M_1 have been compared looking for significant changes. Same for treatments with 2 and 3 application rates. In this comparison, the objective is to catch meaningful changes in the soil hydro-structural parameters values because of different treatments. So, results should tell us which treatment (Chicken, dairy, milorganite) is better in which aspects. Like before first we need to be sure about the homogeneity of variances between replications sets.

6.2.1. Homogeneity of variance test

Folded form F-test has been done for parameters in this type of comparison. Fig. 24, 25 and Fig. 26 show result of the homogeneity test. If variances from 3 groups (Ch, D, M) have not homogeneity in a specific level of confidence, it means variations around the average for each set of replications do not have same error source and practically these groups statistics cannot compare to each other. Here again logarithmic transformation has been done for some of parameters to push the F below the maximum possible value (A_Ema, A_Kst, B_Emi, B_Ema, B_Kst in the application rate of 1 group – A_Kst, B_ΔShC in the rate of 2 group and A_Ema, B_Kst in the rate of 3 group). A_Kip, B_Kip in the rate of 2 group F-statistics replaced by 200 and ignored because of same reason explained in previous comparison type. At the end, all parameters and their transferred display homogeneity and qualified to variance analysis.

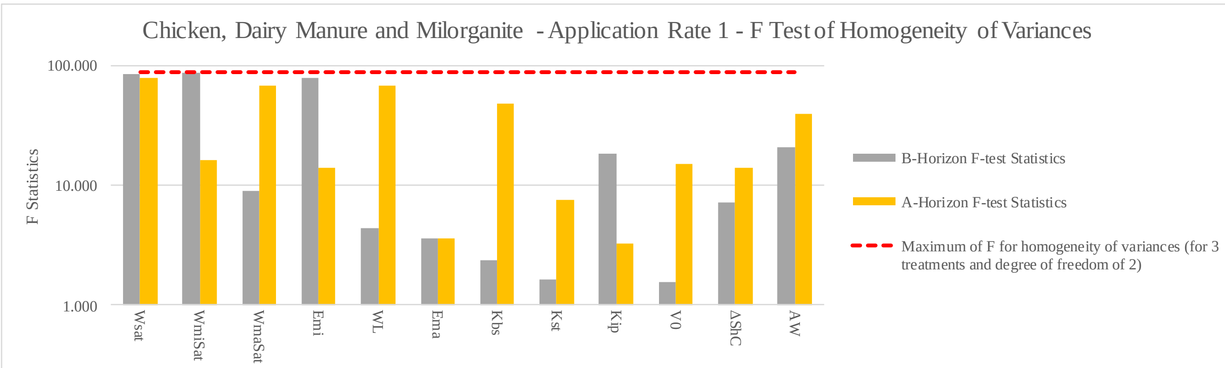

Fig. 24. Test of homogeneity for samples of plots with different treatment and application rate of 1

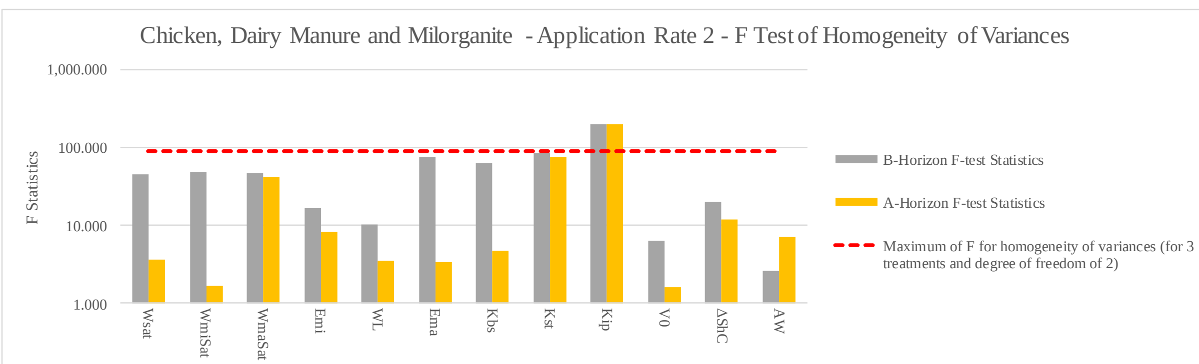

Fig. 25. Test of homogeneity for samples of plots with different treatment and application rate of 2

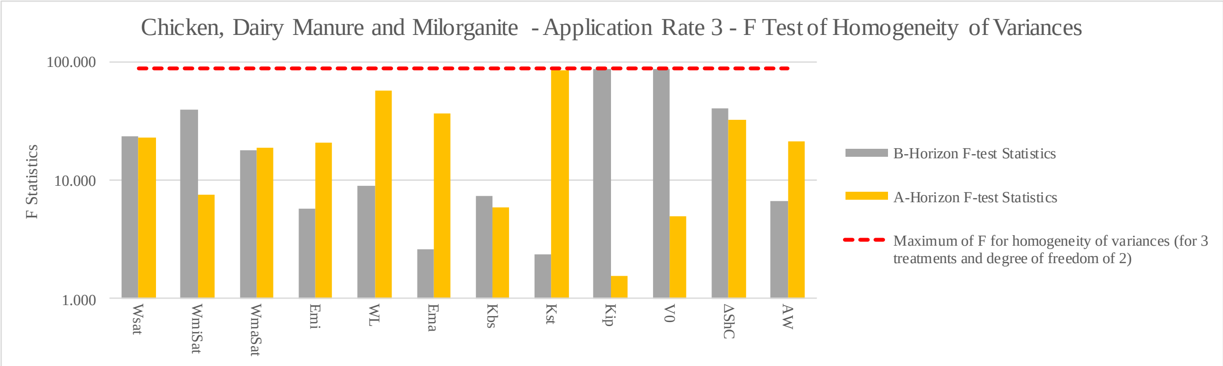

Fig. 26. Test of homogeneity for samples of plots with different treatment and application rate of 3

6.2.2. Significance analysis

Fig. 27, 28 and Fig. 29. show significances of differences in parameters because of changing the treatment with the same application rate.

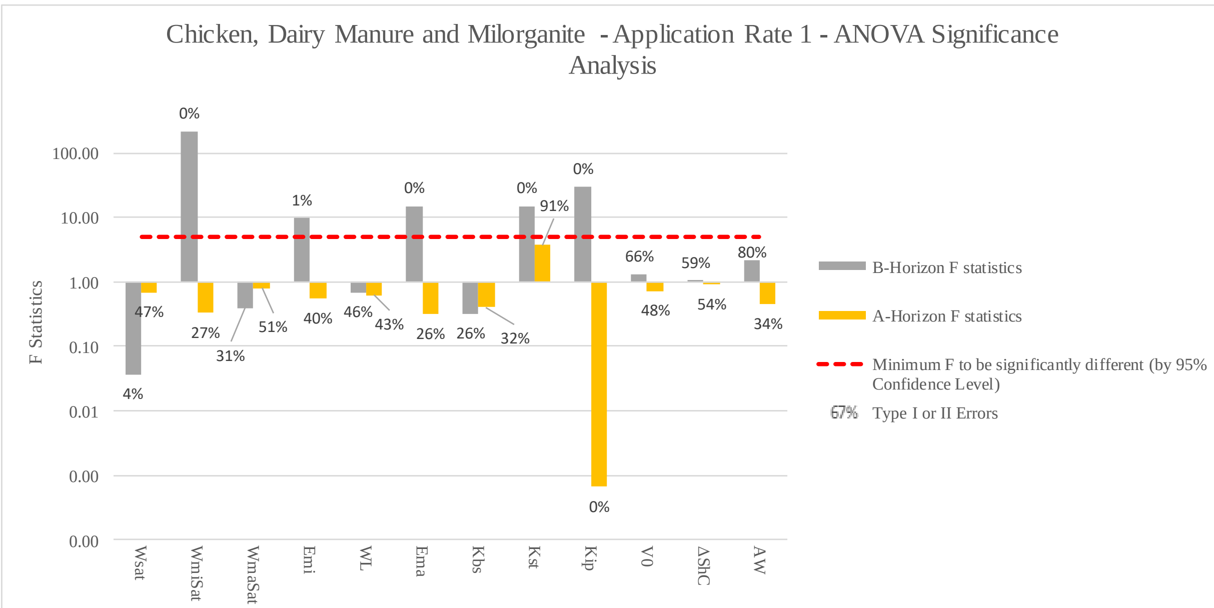

Fig. 27. Three sets of samples with different treatments and application rate of 1 compared – The red dashed line shows the minimum of F statistics to be significantly different. Parameters that crossed the line imply the fact that the parameter of at least one set has changed significantly by 95% level of confidence.

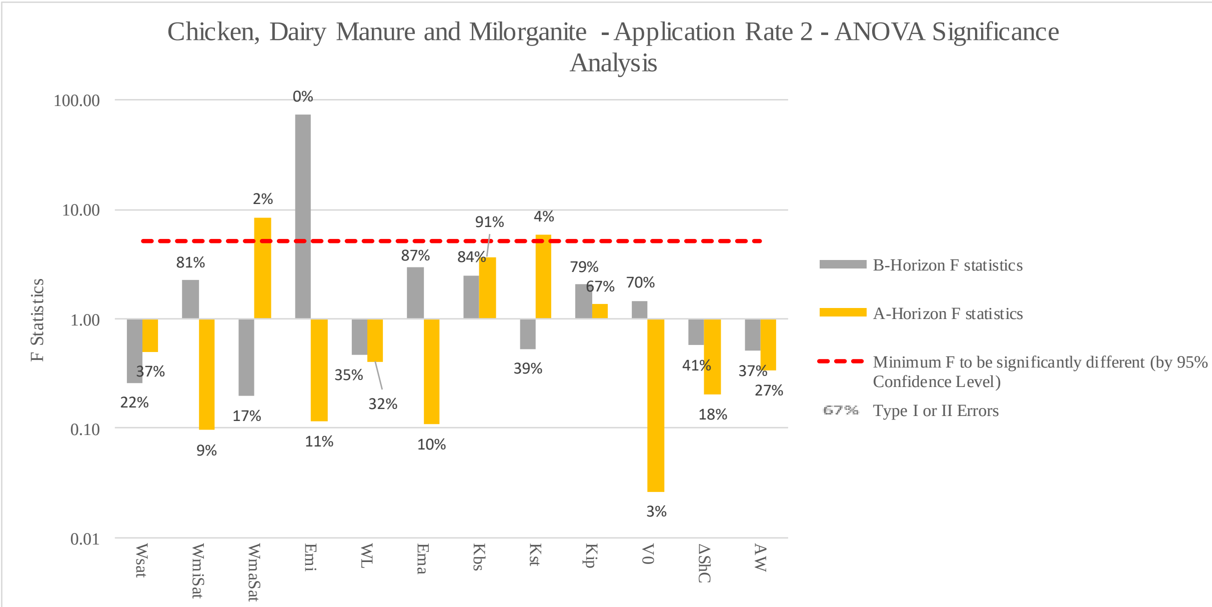

Fig. 28. Three sets of samples with different treatments and application rate of 2 compared – The red dashed line shows the minimum of F statistics to be significantly different. Parameters that crossed the line imply the fact that the parameter of at least one set has changed significantly by 95% level of confidence.

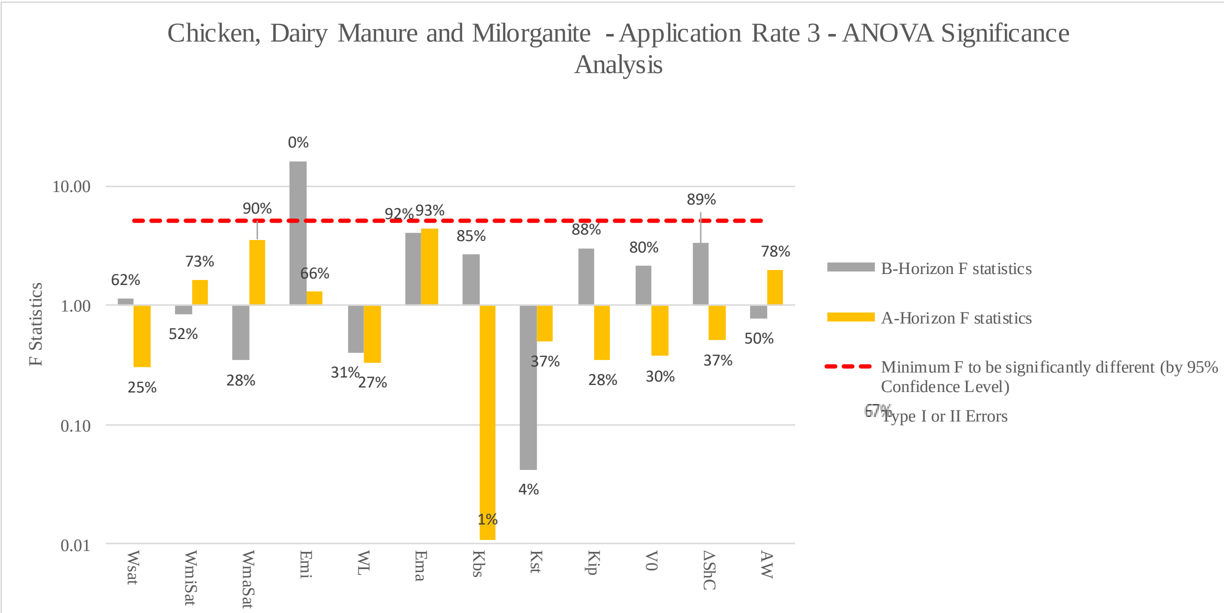

Fig. 29. Three sets of samples with different treatments and application rate of 3 compared – The red dashed line shows the minimum of F statistics to be significantly different. Parameters that crossed the line imply the fact that the parameter of at least one set has changed significantly by 95% level of confidence.

6.2.3. Parameter evaluation

The measured soil shrinkage curves and water retention curves for all treatment types with the same application rates at different horizon can be seen in Figure 30, Figure 31 and Figure 32. The average values of hydro-structural parameters also can be found in table A.7 in the appendix. Like the previous comparison, by putting qualitative interpretations beside quantitative probabilities that have been calculated for each parameter in the statistics section can give a rational explanation about each scenario. In this type of comparison, interpretations are mostly focused on changes in the treatment type and the objective is not to compare different rates effects with each other which was discussed before.

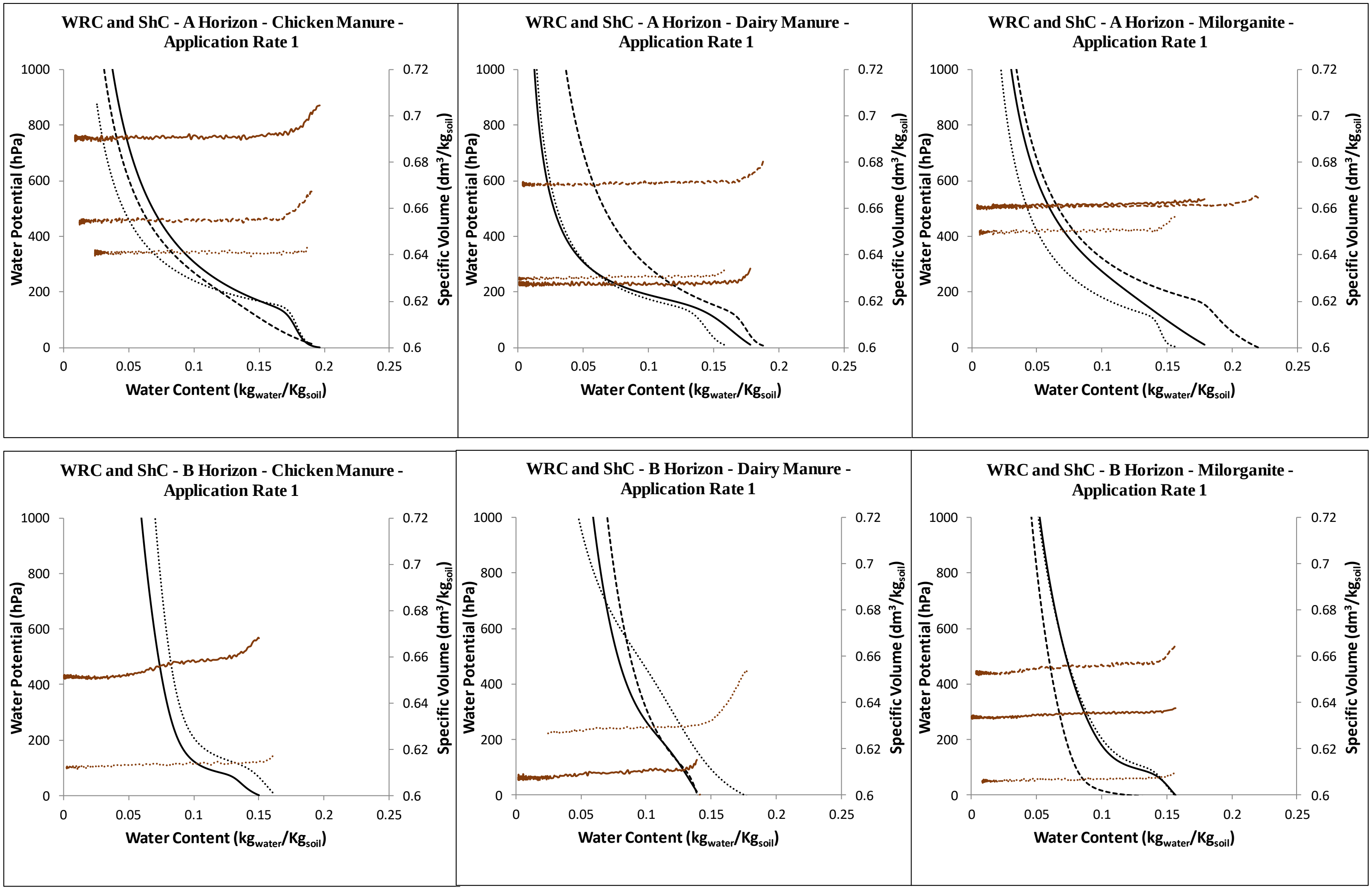

Fig. 30. Representative shrinkage curves (maroon) and soil water retention curves (black) for horizon A (top row) and B (down row) samples with 1 application rate and different application treatments

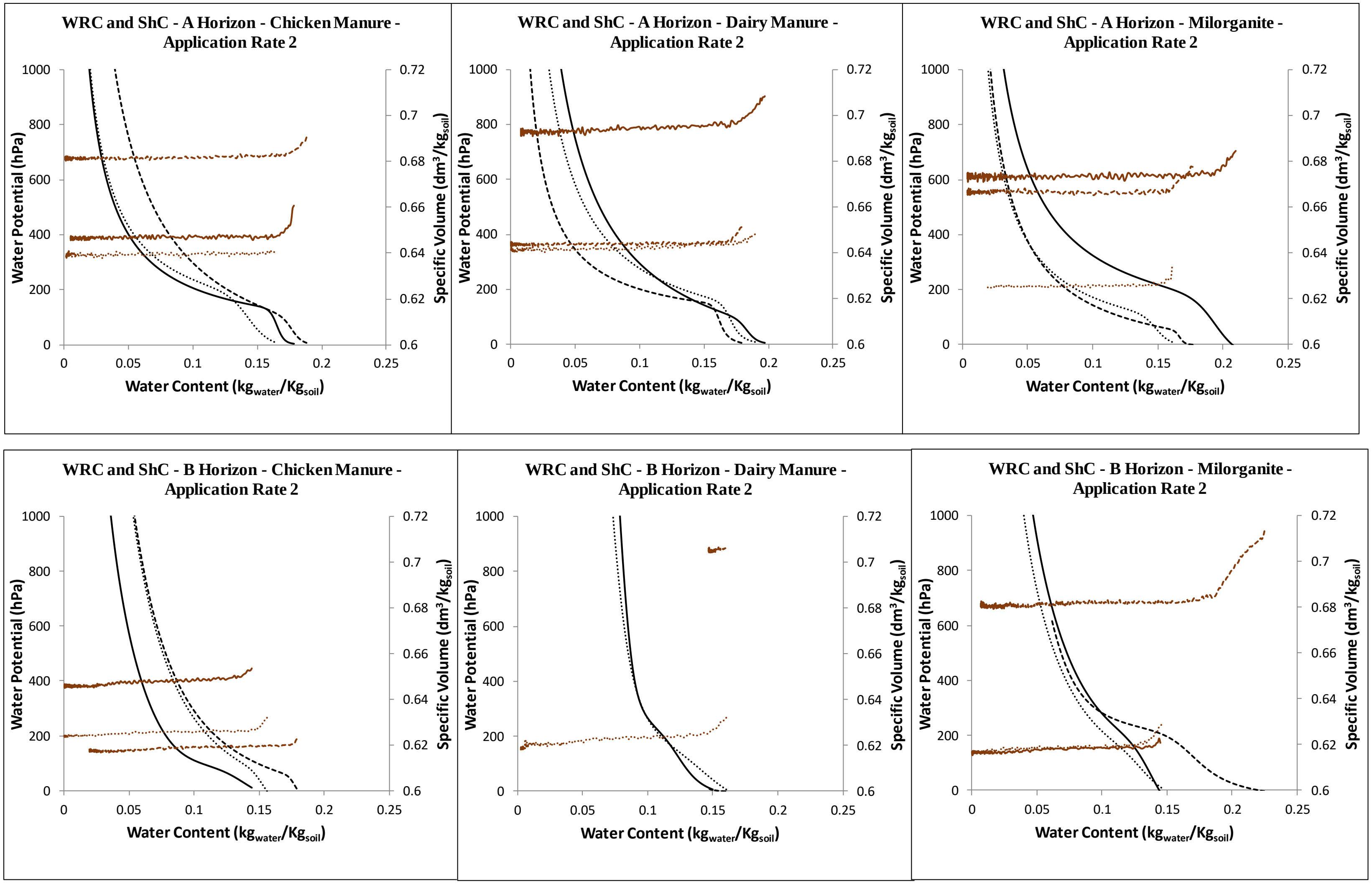

Fig. 31. Representative shrinkage curves (maroon) and soil water retention curves (black) for horizon A (top row) and B (down row) samples with 2 application rate and different application treatments

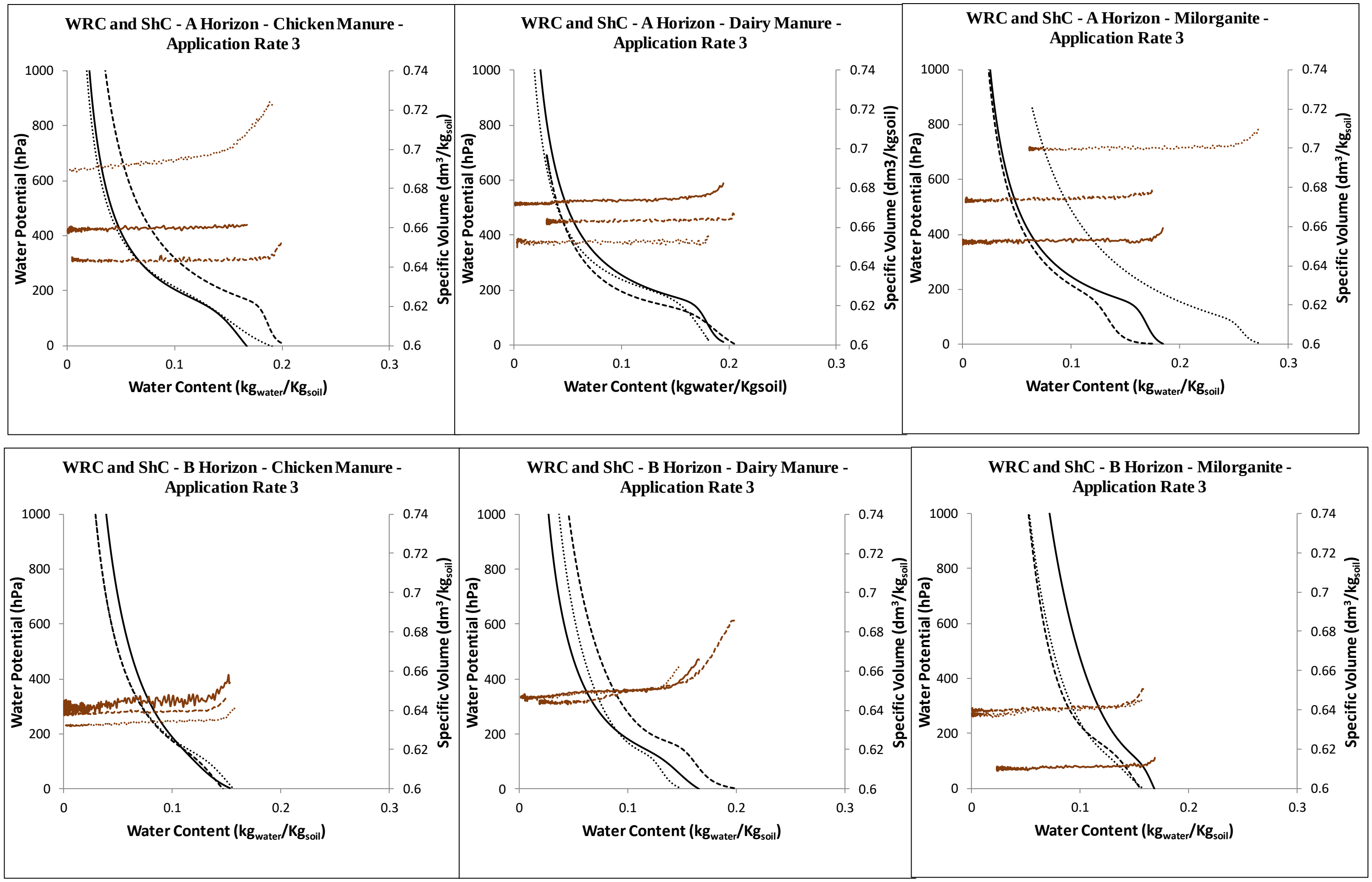

Fig. 32. Representative shrinkage curves (maroon) and soil water retention curves (black) for horizon A (top row) and B (down row) samples with 3 application rate and different application treatments

6.2.3.1.Soil shrinkage curves

By comparing ShC curves in three application rate cases for different treatments, generally it seems chicken manure treatment, in rate 1 at both horizons shows greater specific volume in average throughout the drying process compare to other treatments in the same rate. In rate 2, dairy manure has a greater specific volume in comparison with the other treatments. In rate 3, milorganite has greater specific volume in A- horizon but cannot say the same thing about the B horizon. What are worthy to mention is a good aggregate structure revealed in rate 2 for milorganite and rate 3 for dairy manure. For having any hypothesis in this matter first it's required to check other parameters.

6.2.3.2. Variation in characteristic parameters of the soil aggregates structure

Looking at K_{bs} and K_{st} significance analysis and their values, comparing treatments in each rate (Fig. 33,34), generally in B horizon, aggregate structures are stronger. The changes in rate_1 are not significant, in rate_2 changes for both horizons are moderately significant. Therefore, dairy manure shows a better aggregate structure in rate_2. In rate_3, only in B horizon, k_{bs} changed moderately significant for different treatment types and again dairy manure shows better aggregate structure. ΔShC and V_0 are other soil shrinkage curve variable that directly related to aggregate structural characteristics and these parameters do not show a significant difference except for dairy manure in rate 3 which shows a moderate significant ΔShC (larger value).

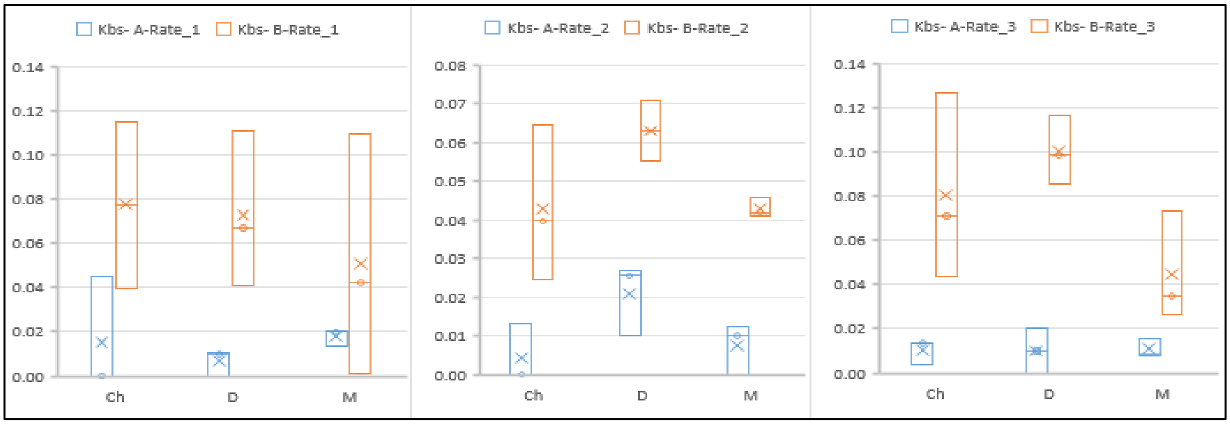

Fig. 33. K_{bs} changes in 3 treatments at different rates

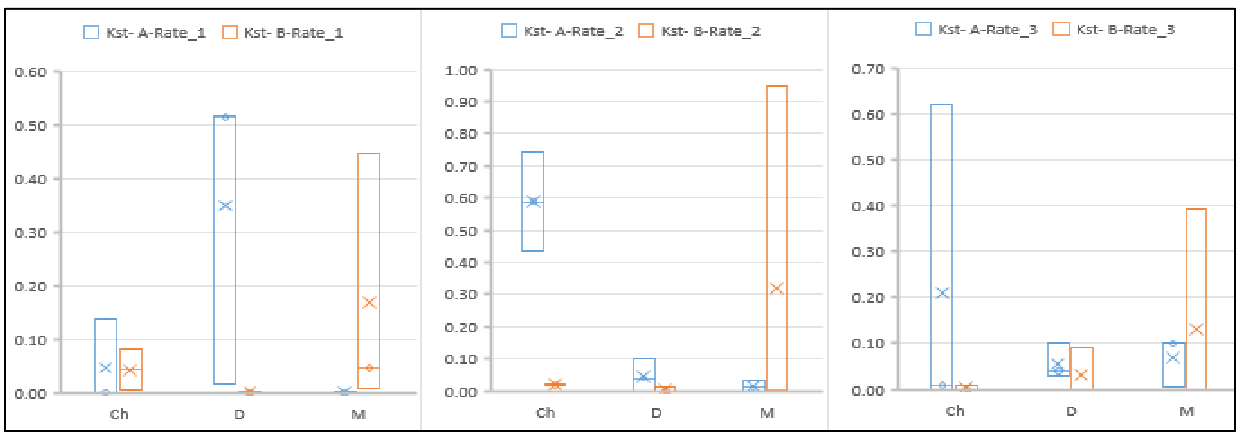

Fig. 34. K_{st} changes in 3 treatments at different rates

6.2.3.3. **Water retention curve**

Water retention curves have been presented in Figure 30, Figure 31 and Figure 32 as before, in black lines.

6.2.3.4. Variation in characteristic parameters of the soil water holding properties

W_L is the water content at the point that all interpedal water has drained. Therefore it's a combination of macro, micropore water content and residual water. Looking at its variation in Figure 35 and its statistics reveal that there are no significant changes between treatments for both horizons.

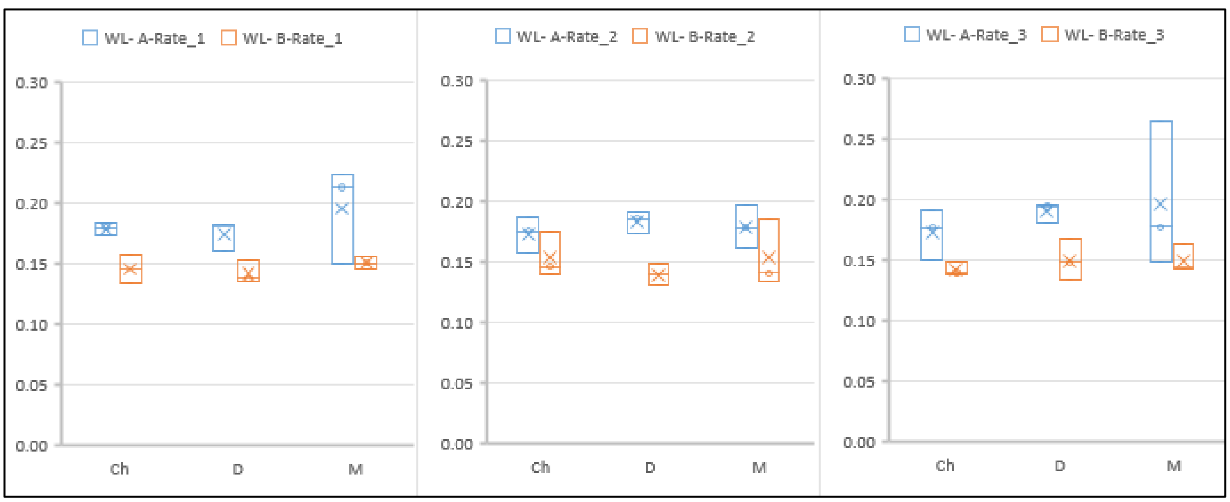

Fig. 35. W_L changes in 3 treatments at different rates

Macropore water content is the water stored between the primary peds. Its statistics for this type of comparison shows significant differences for A-Horizon in rate_2 but insignificancy for B-Horizon. Rate_3 also shows moderate significance for again dairy manure treatment samples that contain more macropore water in A-horizon (Figure 36).

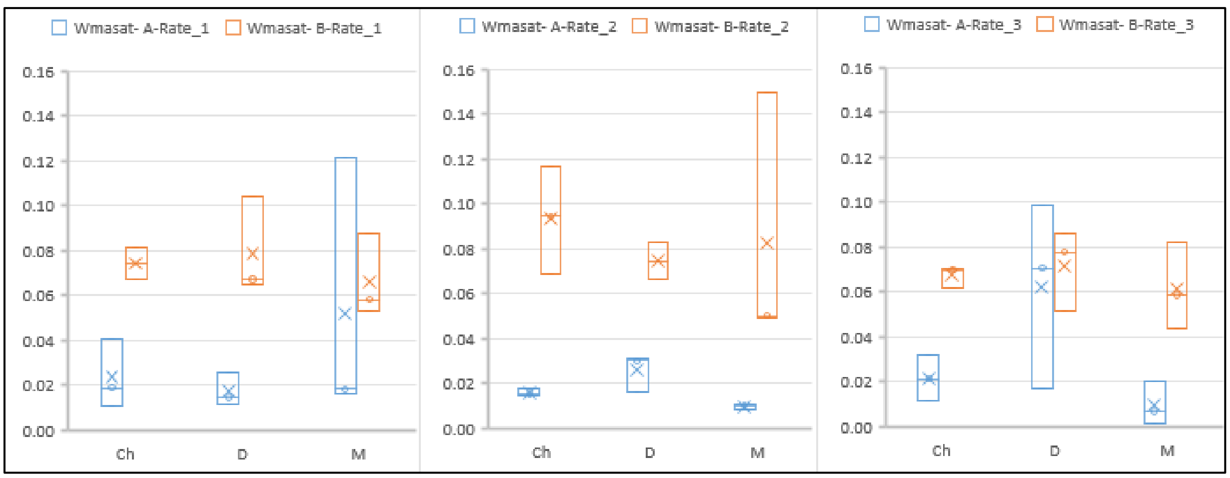

Fig. 36. Macropore volume water content at saturation changes in 3 treatments with different rates

The potential energy on the external surface of the primary peds, E_{ma} value is presented in Figure 37. In rate_1 and B horizon dairy manure shows significant differences. But in rate_2 and 3, horizon B chicken manure showed more E_{ma} in compare to other treatments.

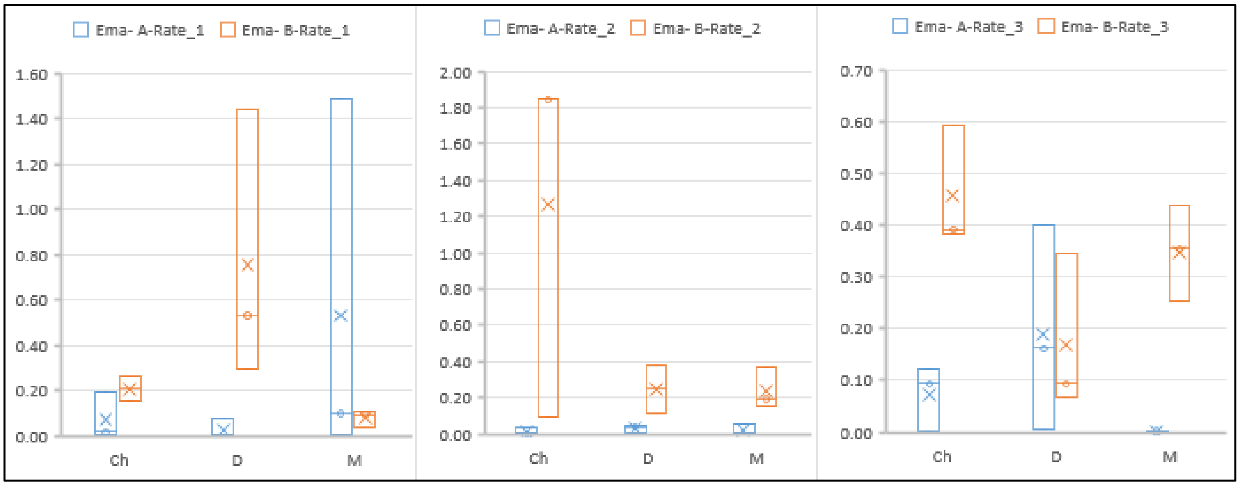

Fig. 37. E_{ma} changes in 3 treatments with different rates

In micropore part (Figure 38), water content again has a total reverse story. Horizon A generally contains more micropore water. But for this parameter, any major significant difference does not exist between treatments.

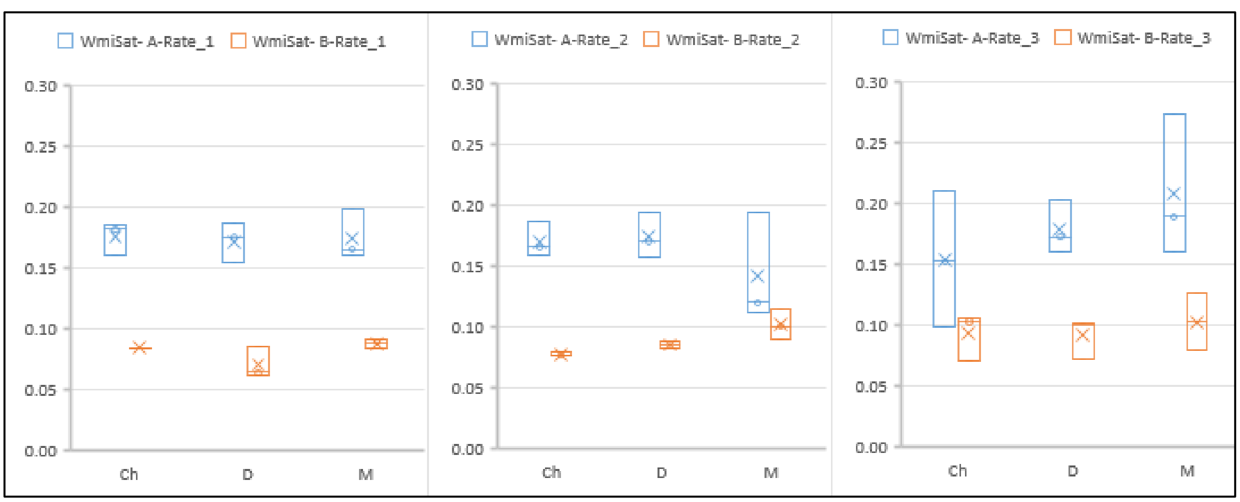

Fig. 38. Micropore volume water content at saturation changes in 3 treatments with different rates

E_{mi} variations are in Figure 39. This parameter shows significant magnitude in the case of chicken manure in rate_1, Dairy manure in rate_2 and milorganite in rate_3 all in B horizon. Dairy manure in B horizon, however, is a lot more significant than other differences.

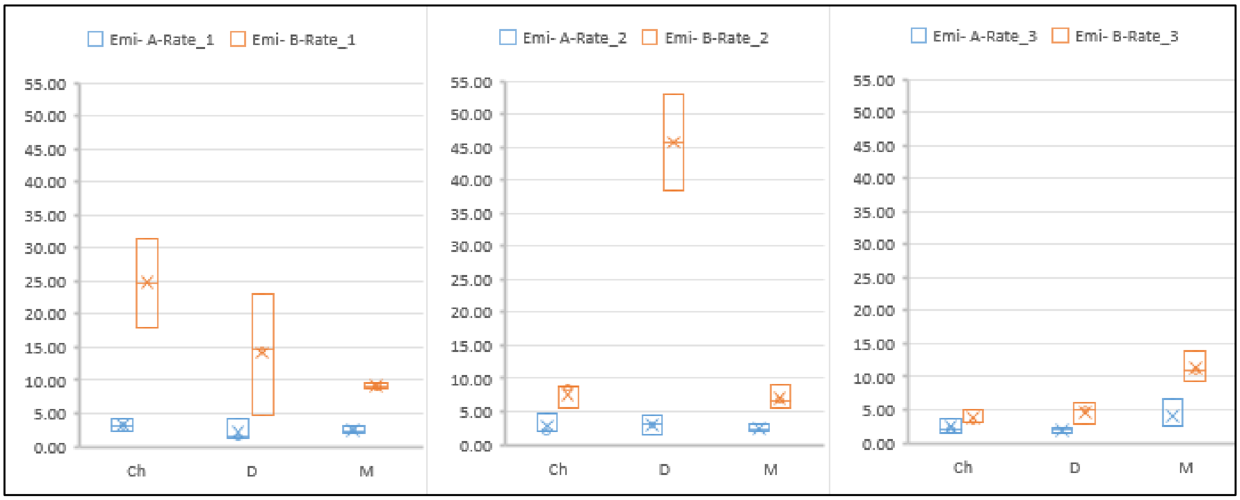

Fig. 39. E_{mi} changes in 3 treatments with different rates

The other parameter related to soil holding properties is AW. Looking at AW statistics and Figure 40, AW has not revealed any statistically significant differences between different treatments.

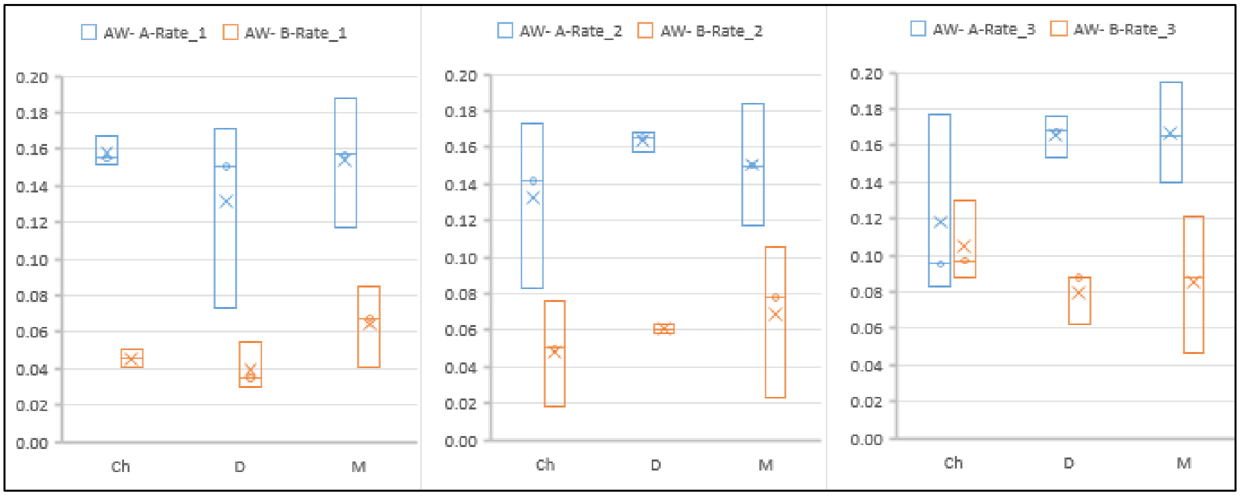

Fig. 40. AW changes in 3 treatments at different rates

6.3. Outcomes analysis and feasibility of soil quality indicator definition

Table 8 shows the outcome of application rate comparison and table 9 is the outcomes of treatments comparison.

In application rate comparison, it's clear that except for dairy manure (which needs more sampling) increasing the rate of application from 168 to 672 KgN/ha doesn't show significant effects and didn't change aggregate structural parameters of the soil. However, using treatments in comparison to not using it (control samples) enhanced at least specific volume, water content and available water in A horizon for plants. This increase is because of potential energies of the surface charges of organic matter that enhanced the structure of the soil in a way that more water has been retained in micropore spaces. Also, application rate 3 (672 KgN/ha) has affected available water of B horizon for Chicken and Dairy manure.

Table 8. Summing up results of comparison by different application rates

			Chicken Manure		Dairy Manure		Milorganite	
			A	B	A	B	A	B
Specific Volume			Increased By increasing the application rate					
Aggregate Structure Parameters	K_{bs}	Significance	-	-	-	-	-	-
		Change						
	K_{st}	Significance	×	×	-	-	×	-
		Change						
	V_0	Significance	×	-	-	+	-	-
		Change				Rate3		
	ΔShC	Significance	-	-	-	-	×	-
		Change						
Water Content Parameters	W_{maSat}	Significance	+	×	+	-	+	-
		Change	Rate0		Rate0		Rate0	
	E_{ma}	Significance	+	-	×	-	+	+
		Change	Rate0		Rate0		Rate0	
	W_{miSat}	Significance	+	-	+	+	+	-
		Change	Rate0		Rate0	↗	Rate0	
	E_{mi}	Significance	+	+	-	+	×	×
		Change	Rate0	Rate1		Rate2	Rate0	
	W_L	Significance	-	-	-	-	-	-
		Change						
AW		Significance	+	+	+	+	+	-
		Change	Rate0	Rate3	Rate0	Rate3	Rate0	

Table 9. Summing up of results of comparison between treatments

			Rate1		Rate2		Rate3	
			A	B	A	B	A	B
Specific Volume		Significance	CH		D		M	-
Aggregate Structure Parameters	K_{bs}	Significance	-	-	×	×	-	×
		Change			D			D
	K_{st}	Significance	×	+	+	-	-	-
		Change	D	M	CH			
	V_0	Significance	-	-	-	-	-	×
		Change						D
	ΔShC	Significance	-	-	-	-	-	×
		Change						D
Water Content Parameters	W_{maSat}	Significance	-	×	+	-	+	-
		Change			D		D	
	E_{ma}	Significance	-	+	-	×	×	×
		Change		D		CH	D	CH
	W_{miSat}	Significance	-	+	-	×	-	-
		Change				M		
	E_{mi}	Significance	-	+	-	+	-	+
		Change		CH		D		M
	W_L	Significance	-	-	-	-	-	-
		Change						
AW		Significance	-	×	-	-	-	-
		Change						

In table 8, the comparison is between these three treatments. Significance of dairy manure in the aggregate structure is clear and it is more promising to improve soil aggregate structure in rates more than 168 KgN/ha. Putting specific volume results beside E_{mi}, it seems best application rate for chicken manure is rate 1, best for dairy manure is rate 2, and for milorganite is rate 3. However, at the end, available water for these three treatments does not show significant difference. It's worth to mention that E_{mi} has a highly significant value for dairy manure in B horizon at rate 2 and it required more sampling to strengthen the observation that dairy manure is significantly effective in increasing the potential energy of the soil particle surface in horizon B.

Regarding soil quality indicator, defining the soil quality index requires the determination of the properties most sensitive to differences in management practices to allow identification of management outcomes through a set of sensitive soil properties. These soil properties should reflect the capacity of a soil to function correlated to specific management practices. Therefore, there are two reasons that soil quality indicator definition is not possible at this stage of the experiment. First of all, the only sensitive parameter to different management (rate or treatment) is water content parameters (micro and macroporose water content and potential energy). Although these observed variations are important and practical for soil management, since direct aggregate structure parameters variation does not exist, the soil quality indicator model will not be representative of all chemical, biological and physical characteristics of the soil. The duration of the experiment and the nature of the experiment which included mixing of the top layer of soil, first affected the soil aggregate structure (mixing), and not enough time for the aggregate structure to be enhanced (only 6 months) are highly possible reasons for not seeing variation in aggregate structure parameters. However, adding the organic matter helped to increase the potential energy of holding the water and thus increased the water available capacity. The second reason is that there are some other parameters such as crop yield or crop health and organic matter analysis which could strengthen small variation in aggregate structure parameters and cover its lack of significance because of the life of treatment application but these measurements that have been done by other researchers from PVAMU they are not published yet. By fixing a parameter such as organic matter or plant health, it would be possible to define weights to hydro-structural parameters in such a way that gives us a credible combination that products a new soil quality indicator.

7. CONCLUSION AND DISCUSSION

12 hydro-structural parameters selected to conduct the research were enough independent and each one indicates a specific characteristic of the soil aggregate structure or its interaction with water. Regarding the sampling procedure, despite the fact that replications from the same plot were not taken, same treatment and rate values plots examined for location dependency and results showed that parameters are not dependent to location mostly by 95% level and few of them by 99% confidence level. Therefore each 3 counterpart plots considered as replications of a same examination case. Comparisons have been done for 2 scenarios. First looking at the effect of increasing the application rate, and second, looking at treatment type and their effect on hydro-structural parameters. Before starting the parametric evaluation it was necessary to check data statistically. Variance homogeneity as the prerequisite test for variance analysis has been done for both comparisons. This pre-test checks if variances inside each replication set is not significant (replications are homogenous), since the variance between sets is required to be calculated in ANOVA method. Transferring data in few cases gave homogeneity and variance analysis accomplished. Considering the significance of variation for each set of comparisons include type1 error more than 80% gave three categories of changed, unchanged and possibly unchanged. This extra category considering type II error helped a lot in the interpretation process to see the bigger picture in the parametric evaluation.

After analyzing parameters variances, in application rate comparison, it's clear that except for dairy manure (which needs more sampling) increasing the rate of application from 168 to 672 KgN/ha didn't show significant effects and therefore, didn't change aggregate structural parameters of the soil. However, using treatments in comparison to not using it (control samples) enhanced at least specific volume, water content and available water in A horizon for plants. This increase is because of potential energies of the surface charges of organic matter that enhanced the structure of the soil in a way that more water has been retained in micropore spaces. Also, application rate 3 (672 KgN/ha) has affected available water of B horizon for Chicken and Dairy manure.

In the comparison between three treatments, significance of dairy manure in the aggregate structure is clear and it is more promising to improve soil aggregate structure in rates more than 168 KgN/ha. Putting specific volume results beside E_{mi}, it seems best application rate for chicken manure is rate 1, best for dairy manure is rate 2, and for milorganite is rate 3. However, at the end, available water for these three treatments does not show significant difference. It's worth to mention that E_{mi} has a highly significant value for dairy manure in B horizon at rate 2 and it required more sampling to strengthen the observation that dairy manure is significantly effective in increasing the potential energy of the soil particle surface in horizon B.

Defining the soil quality index requires the determination of the properties most sensitive to differences in management practices to allow identification of management outcomes through a set of sensitive soil properties. Therefore, there are two reasons that soil quality indicator definition was not possible at this stage of the experiment. First of all, the only sensitive parameter to different management (rate or treatment) was water content parameters. Although these observed variations are important and practical for soil management, since direct aggregate structure parameters variation does not exist, the soil quality indicator model will not be representative of all chemical, biological and physical characteristics of the soil. The duration of the experiment and the nature of the experiment which included mixing of the top layer of soil, first affected the soil aggregate structure (mixing), and not enough time for the aggregate structure to be enhanced (only 6 months) are highly possible reasons for not seeing variation in aggregate structure parameters. However, adding the organic matter helped to increase the potential energy of holding the water and thus increased the water available capacity. The second reason is that there are some other parameters such as crop yield or crop health and organic matter analysis which could strengthen small variation in aggregate structure parameters and cover its lack of significance because of the life of treatment application. By fixing a parameter such as organic matter or plant health, it would be possible to define weights to hydro-structural parameters in such a way that gives us a credible combination that products a new soil quality indicator. These measurements and analysis are parts of research accomplishing by Prairie View University researchers and have not published yet.

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APPENDIX

Table A. 1. Hydro-structural parameters of samples from chicken manure treatment plots in different application rates, A horizon

Treatment	Unit	A_Ch_0	A_Ch_0	A_Ch_0	A_Ch_1	A_Ch_1	A_Ch_1	A_Ch_2	A_Ch_2	A_Ch_2	A_Ch_3	A_Ch_3	A_Ch_3
Wsat	Kg_{water}/Kg_{soil}	0.20	0.17	0.17	0.20	0.20	0.20	0.19	0.17	0.20	0.18	0.20	0.21
WmiSat	Kg_{water}/Kg_{soil}	0.01	0.01	0.01	0.19	0.18	0.16	0.17	0.15	0.19	0.16	0.16	0.20
Wmasat	Kg_{water}/Kg_{soil}	0.19	0.16	0.16	0.01	0.02	0.04	0.02	0.02	0.01	0.02	0.03	0.01
Emi	Kg_{water}/Kg_{soil}	0.08	0.04	0.05	4.18	2.20	3.10	1.96	1.90	4.60	2.00	1.59	3.72
WL	Kg_{water}/Kg_{soil}	0.17	0.14	0.15	0.18	0.18	0.17	0.17	0.16	0.19	0.18	0.15	0.19
Wip	J/Kg_{solids}	0.04	0.02	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00
Ema	J/Kg_{solids}	1.62	0.68	0.58	0.01	0.02	0.19	0.00	0.03	0.00	0.09	0.12	0.00
Kbs	dm^3/Kg_{water}	0.00	0.01	0.00	0.05	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00
Kst	dm^3/Kg_{water}	0.00	0.02	0.00	0.00	0.00	0.14	0.59	0.43	0.74	0.01	0.62	0.00
Kip	dm^3/Kg_{water}	0.47	0.47	0.20	1.20	0.43	0.81	1.20	0.00	1.20	0.00	0.65	1.11
V0	dm^3/Kg_{soil}	0.57	0.63	0.62	0.69	0.64	0.65	0.65	0.64	0.68	0.66	0.69	0.64
ΔShC	dm^3/Kg_{soil}	0.00	0.01	0.00	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.03	0.01
AW	(Kg_{water}/Kg_{soil})	0.01	0.00	0.00	0.17	0.16	0.15	0.08	0.14	0.17	0.08	0.10	0.18

Table A. 2. Hydro-structural parameters of samples from dairy manure treatment plots in different application rates, A horizon

Treatment	Unit	A_D_0	A_D_0	A_D_0	A_D_1	A_D_1	A_D_1	A_D_2	A_D_2	A_D_2	A_D_3	A_D_3	A_D_3
Wsat	Kg_{water}/Kg_{soil}	0.18	0.21	NA	0.19	0.17	0.20	0.21	0.20	0.19	0.21	0.19	0.21
WmiSat	Kg_{water}/Kg_{soil}	0.01	0.02	NA	0.16	0.16	0.19	0.19	0.17	0.16	0.19	0.12	0.11
Wmasat	Kg_{water}/Kg_{soil}	0.17	0.19	NA	0.03	0.01	0.01	0.02	0.03	0.03	0.02	0.07	0.10
Emi	Kg_{water}/Kg_{soil}	0.16	0.40	NA	1.11	1.39	4.10	4.57	3.00	1.40	2.40	1.37	2.10
WL	Kg_{water}/Kg_{soil}	0.17	0.20	NA	0.18	0.16	0.18	0.19	0.17	0.19	0.19	0.18	0.19
Wip	J/Kg_{solids}	0.03	0.04	NA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Ema	J/Kg_{solids}	1.22	2.89	NA	0.07	0.00	0.00	0.00	0.04	0.04	0.01	0.40	0.16
Kbs	dm^3/Kg_{water}	0.02	0.01	NA	0.00	0.01	0.01	0.03	0.03	0.01	0.01	0.00	0.02
Kst	dm^3/Kg_{water}	0.00	0.01	NA	0.02	0.51	0.52	0.10	0.04	0.00	0.10	0.04	0.03
Kip	dm^3/Kg_{water}	0.12	1.20	NA	1.20	0.00	1.20	1.20	0.22	0.00	1.20	0.00	0.00
V0	dm^3/Kg_{soil}	0.65	0.67	NA	0.63	0.63	0.67	0.69	0.64	0.64	0.67	0.65	0.66
ΔShC	dm^3/Kg_{soil}	0.00	0.01	0.00	0.01	0.00	0.01	0.02	0.01	0.01	0.01	0.01	0.01
AW	(Kg_{water}/Kg_{soil})	0.00	0.01	NA	0.15	0.07	0.17	0.16	0.17	0.17	0.18	0.17	0.15

Table A. 3. Hydro-structural parameters of samples from milorganite treatment plots in different application rates, A horizon

Treatment	Unit	A_M_0	A_M_0	A_M_0	A_M_1	A_M_1	A_M_1	A_M_2	A_M_2	A_M_2	A_M_3	A_M_3	A_M_3
Wsat	Kg_{water}/Kg_{soil}	0.19	0.20	0.20	0.23	0.17	0.22	0.21	0.17	0.18	0.19	0.28	0.18
WmiSat	Kg_{water}/Kg_{soil}	0.02	0.02	0.05	0.21	0.15	0.10	0.20	0.16	0.17	0.19	0.27	0.16
Wmasat	Kg_{water}/Kg_{soil}	0.17	0.18	0.14	0.02	0.02	0.12	0.01	0.01	0.01	0.00	0.01	0.02
Emi	Kg_{water}/Kg_{soil}	0.23	0.21	0.18	2.98	2.40	2.11	3.10	2.02	2.33	2.61	6.74	2.48
WL	Kg_{water}/Kg_{soil}	0.26	0.15	0.17	0.22	0.15	0.21	0.20	0.16	0.18	0.18	0.26	0.15
Wip	J/Kg_{solids}	0.01	0.02	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00
Ema	J/Kg_{solids}	0.86	0.80	0.08	0.10	0.00	1.49	0.06	0.01	0.00	0.00	0.00	0.00
Kbs	dm^3/Kg_{water}	0.00	0.04	0.03	0.02	0.02	0.01	0.01	0.00	0.01	0.01	0.01	0.02
Kst	dm^3/Kg_{water}	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.01	0.10	0.10
Kip	dm^3/Kg_{water}	0.00	0.15	1.20	0.00	1.20	0.00	1.20	1.20	1.20	1.20	1.20	0.09
V0	dm^3/Kg_{soil}	0.63	0.66	0.59	0.66	0.65	0.66	0.67	0.63	0.67	0.65	0.70	0.67
ΔShC	dm^3/Kg_{soil}	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01
AW	(Kg_{water}/Kg_{soil})	0.00	0.01	0.00	0.16	0.12	0.19	0.18	0.12	0.15	0.17	0.19	0.14

Table A. 4. Hydro-structural parameters of samples from chicken manure treatment plots in different application rates- B horizon

Treatment	B_Ch_0	B_Ch_0	B_Ch_0	B_Ch_1	B_Ch_1	B_Ch_1	B_Ch_2	B_Ch_2	B_Ch_2	B_Ch_3	B_Ch_3	B_Ch_3
Wsat	0.170	0.169	0.150	0.150	0.165	NA	0.153	0.156	0.180	0.153	0.160	0.150
WmiSat	0.079	0.073	0.074	0.083	0.083	NA	0.084	0.061	0.064	0.083	0.090	0.088
Wmasat	0.091	0.095	0.076	0.067	0.082	NA	0.069	0.094	0.116	0.070	0.070	0.062
Emi	13.834	3.219	11.842	18.000	31.466	NA	5.537	8.656	8.656	4.865	3.137	3.200
WL	0.156	0.146	0.138	0.133	0.156	NA	0.139	0.145	0.174	0.137	0.148	0.139
Wip	0.011	0.005	0.029	0.012	0.011	NA	0.007	0.042	0.042	0.028	0.015	0.015
Ema	0.501	0.237	0.789	0.149	0.261	NA	0.098	1.844	1.844	0.593	0.383	0.390
Kbs	0.055	0.061	0.016	0.115	0.040	NA	0.065	0.040	0.024	0.126	0.071	0.044
Kst	0.020	0.020	0.020	0.080	0.004	NA	0.015	0.018	0.023	0.000	0.010	0.000
Kip	1.200	0.978	0.343	0.741	0.961	NA	1.200	1.200	1.200	0.978	1.200	1.200
V0	0.573	0.637	0.617	0.651	0.612	NA	0.645	0.624	0.617	0.640	0.631	0.638
ΔShC	0.010	0.011	0.006	0.016	0.005	NA	0.007	0.008	0.005	0.014	0.009	0.007
AW	0.06	0.06	0.09	0.05	0.04	NA	0.08	0.05	0.02	0.09	0.13	0.10

Table A. 5. Hydro-structural parameters of samples from dairy manure treatment plots in different application rates- B horizon

Treatment	B_D_0	B_D_0	B_D_0	B_D_1	B_Ch_1	B_Ch_1	B_D_2	B_D_2	B_D_2	B_D_3	B_D_3	B_D_3
Wsat	0.152	0.152	NA	0.145	0.180	0.140	0.153	0.165	NA	0.167	0.151	0.200
WmiSat	0.078	0.078	NA	0.078	0.076	0.075	0.087	0.082	NA	0.089	0.100	0.114
Wmasat	0.074	0.074	NA	0.067	0.104	0.065	0.066	0.083	NA	0.078	0.052	0.086
Emi	5.206	19.909	NA	14.590	4.768	23.190	53.048	38.381	NA	2.813	4.967	6.200
WL	0.136	0.133	NA	0.134	0.152	0.137	0.130	0.148	NA	0.147	0.133	0.166
Wip	0.000	0.011	NA	0.013	0.005	0.024	0.004	0.015	NA	0.016	0.004	0.005
Ema	0.188	0.721	NA	0.528	0.297	1.442	0.115	0.382	NA	0.344	0.066	0.093
Kbs	0.084	0.059	NA	0.111	0.067	0.041	0.055	0.071	NA	0.098	0.086	0.117
Kst	0.022	0.024	NA	0.000	0.000	0.000	0.000	0.010	NA	0.000	0.000	0.092
Kip	1.025	1.200	NA	1.200	1.200	1.095	0.099	0.906	NA	1.117	1.200	1.200
V0	0.594	0.598	NA	0.606	0.627	0.590	0.589	0.620	NA	0.646	0.646	0.643
ΔShC	0.008	0.012	NA	0.008	0.027	0.009	0.006	0.014	NA	0.017	0.015	0.041
AW	0.058	0.043	NA	0.054	0.035	0.030	0.063	0.059	NA	0.088	0.088	0.063

Table A. 6. Hydro-structural parameters of samples from milorganite treatment plots in different application rates- B horizon

Treatment	B_M_0	B_M_0	B_M_0	B_M_1	B_M_1	B_M_1	B_M_2	B_M_2	B_M_2	B_M_3	B_M_3	B_M_3
Wsat	0.160	0.160	0.150	0.160	0.157	0.157	0.150	0.150	0.220	0.170	0.160	0.160
WmiSat	0.101	0.102	0.070	0.102	0.105	0.069	0.101	0.100	0.071	0.126	0.102	0.078
Wmasat	0.059	0.058	0.080	0.058	0.053	0.088	0.049	0.050	0.149	0.044	0.058	0.082
Emi	6.500	9.069	9.069	9.548	8.794	9.000	6.684	5.424	9.069	13.837	9.176	10.880
WL	0.143	0.148	0.136	0.156	0.150	0.145	0.140	0.133	0.185	0.162	0.143	0.142
Wip	0.010	0.014	0.014	0.005	0.006	0.006	0.005	0.007	0.014	0.012	0.013	0.013
Ema	0.178	0.248	0.369	0.090	0.104	0.039	0.191	0.148	0.369	0.354	0.251	0.439
Kbs	0.059	0.083	0.050	0.042	0.001	0.109	0.046	0.041	0.042	0.035	0.073	0.027
Kst	0.000	0.000	0.952	0.007	0.046	0.447	0.000	0.003	0.950	0.000	0.000	0.393
Kip	0.885	0.952	0.012	0.000	0.447	0.000	1.199	0.950	0.005	1.200	0.393	0.024
V0	0.613	0.609	0.592	0.633	0.606	0.653	0.616	0.617	0.680	0.609	0.636	0.640
ΔShC	0.009	0.008	0.004	0.004	0.003	0.011	0.004	0.012	0.032	0.005	0.008	0.010
AW	0.088	0.079	0.046	0.085	0.068	0.040	0.078	0.106	0.023	0.121	0.088	0.046

Table A. 7. The average of hydro-structural parameters of samples from all treatment plots in different application rates- A and B horizon

Treatment	Unit	A_Ch_0	A_Ch_1	A_Ch_2	A_Ch_3	B_Ch_0	B_Ch_1	B_Ch_2	B_Ch_3
Wsat	Kg_{water}/Kg_{soil}	0.178 ± 0.016	0.199 ± 0.002	0.187 ± 0.015	0.196 ± 0.015	0.163 ± 0.011	0.158 ± 0.011	0.163 ± 0.015	0.154 ± 0.005
WmiSat	Kg_{water}/Kg_{soil}	0.008 ± 0.003	0.175 ± 0.014	0.171 ± 0.017	0.174 ± 0.021	0.075 ± 0.003	0.083 ± 0	0.07 ± 0.013	0.087 ± 0.004
Wmasat	Kg_{water}/Kg_{soil}	0.169 ± 0.017	0.023 ± 0.015	0.016 ± 0.002	0.022 ± 0.01	0.087 ± 0.01	0.074 ± 0.01	0.093 ± 0.024	0.067 ± 0.005
Emi	Kg_{water}/Kg_{soil}	0.058 ± 0.02	3.159 ± 0.99	2.818 ± 1.543	2.436 ± 1.132	9.631 ± 5.642	24.733 ± 9.522	7.616 ± 1.8	3.734 ± 0.98
WL	Kg_{water}/Kg_{soil}	0.152 ± 0.014	0.178 ± 0.005	0.172 ± 0.015	0.172 ± 0.02	0.146 ± 0.009	0.145 ± 0.016	0.153 ± 0.018	0.141 ± 0.006
Wip	J/Kg_{solids}	0.024 ± 0.013	0.004 ± 0.005	0.001 ± 0.001	0.003 ± 0.003	0.015 ± 0.012	0.012 ± 0.001	0.03 ± 0.02	0.019 ± 0.008
Ema	J/Kg_{solids}	0.958 ± 0.573	0.071 ± 0.102	0.012 ± 0.017	0.073 ± 0.063	0.509 ± 0.276	0.205 ± 0.079	1.262 ± 1.008	0.455 ± 0.12
Kbs	dm^3/Kg_{water}	0.003 ± 0.006	0.015 ± 0.026	0.004 ± 0.008	0.01 ± 0.006	0.044 ± 0.024	0.077 ± 0.053	0.043 ± 0.02	0.08 ± 0.042
Kst	dm^3/Kg_{water}	0.005 ± 0.009	0.046 ± 0.079	0.587 ± 0.155	0.209 ± 0.354	0.02 ± 0	0.042 ± 0.054	0.019 ± 0.004	0.003 ± 0.006
Kip	dm^3/Kg_{water}	0.381 ± 0.157	0.816 ± 0.383	0.8 ± 0.693	0.587 ± 0.559	0.84 ± 0.445	0.851 ± 0.156	1.2 ± 0	1.126 ± 0.128
V0	dm^3/Kg_{soil}	0.604 ± 0.033	0.662 ± 0.025	0.655 ± 0.023	0.664 ± 0.023	0.609 ± 0.033	0.632 ± 0.028	0.629 ± 0.015	0.636 ± 0.005
ΔShC	dm^3/Kg_{soil}	0.005 ± 0.003	0.009 ± 0.006	0.008 ± 0.007	0.015 ± 0.017	0.009 ± 0.003	0.011 ± 0.008	0.007 ± 0.001	0.01 ± 0.003
AW	(Kg_{water}/Kg_{soil})	0.003 ± 0.003	0.158 ± 0.008	0.132 ± 0.046	0.118 ± 0.051	0.068 ± 0.021	0.045 ± 0.007	0.048 ± 0.029	0.105 ± 0.022
Treatment	**Unit**	**A_D_0**	**A_D_1**	**A_D_2**	**A_D_3**	**B_D_0**	**B_D_1**	**B_D_2**	**B_D_3**
Wsat	Kg_{water}/Kg_{soil}	0.197 ± 0.025	0.187 ± 0.015	0.199 ± 0.012	0.203 ± 0.012	0.152 ± 0	0.155 ± 0.022	0.159 ± 0.008	0.173 ± 0.025
WmiSat	Kg_{water}/Kg_{soil}	0.016 ± 0.005	0.17 ± 0.014	0.173 ± 0.019	0.142 ± 0.045	0.078 ± 0	0.076 ± 0.001	0.085 ± 0.004	0.101 ± 0.012
Wmasat	Kg_{water}/Kg_{soil}	0.181 ± 0.02	0.017 ± 0.007	0.026 ± 0.008	0.062 ± 0.041	0.074 ± 0	0.079 ± 0.022	0.074 ± 0.012	0.072 ± 0.018
Emi	Kg_{water}/Kg_{soil}	0.281 ± 0.168	2.203 ± 1.652	2.989 ± 1.582	1.954 ± 0.531	12.557 ± 10.396	14.183 ± 9.218	45.714 ± 10.371	4.66 ± 1.715
WL	Kg_{water}/Kg_{soil}	0.185 ± 0.025	0.174 ± 0.013	0.183 ± 0.01	0.19 ± 0.008	0.135 ± 0.003	0.141 ± 0.01	0.139 ± 0.013	0.149 ± 0.017
Wip	J/Kg_{solids}	0.034 ± 0.009	0.001 ± 0.002	0.002 ± 0.001	0.007 ± 0.006	0.005 ± 0.007	0.014 ± 0.01	0.01 ± 0.007	0.009 ± 0.007
Ema	J/Kg_{solids}	2.056 ± 1.185	0.027 ± 0.039	0.028 ± 0.023	0.189 ± 0.2	0.455 ± 0.376	0.756 ± 0.606	0.248 ± 0.188	0.168 ± 0.153
Kbs	dm^3/Kg_{water}	0.014 ± 0.002	0.007 ± 0.006	0.021 ± 0.009	0.01 ± 0.01	0.071 ± 0.017	0.073 ± 0.035	0.063 ± 0.011	0.1 ± 0.015
Kst	dm^3/Kg_{water}	0.005 ± 0.005	0.349 ± 0.288	0.046 ± 0.05	0.056 ± 0.038	0.023 ± 0.002	0 ± 0	0.005 ± 0.007	0.031 ± 0.053
Kip	dm^3/Kg_{water}	0.661 ± 0.762	0.8 ± 0.693	0.471 ± 0.638	0.4 ± 0.693	1.112 ± 0.124	1.165 ± 0.06	0.503 ± 0.571	1.172 ± 0.048
V0	dm^3/Kg_{soil}	0.66 ± 0.011	0.642 ± 0.024	0.659 ± 0.029	0.661 ± 0.011	0.596 ± 0.003	0.608 ± 0.019	0.605 ± 0.022	0.645 ± 0.002
ΔShC	dm^3/Kg_{soil}	0.005 ± 0.004	0.007 ± 0.003	0.01 ± 0.005	0.007 ± 0.003	0.01 ± 0.003	0.015 ± 0.011	0.01 ± 0.006	0.024 ± 0.014
AW	(Kg_{water}/Kg_{soil})	0.007 ± 0.006	0.132 ± 0.052	0.164 ± 0.006	0.166 ± 0.011	0.051 ± 0.011	0.04 ± 0.013	0.061 ± 0.003	0.079 ± 0.014
Treatment	**Unit**	**A_M_0**	**A_M_1**	**A_M_2**	**A_M_3**	**B_M_0**	**B_M_1**	**B_M_2**	**B_M_3**
Wsat	Kg_{water}/Kg_{soil}	0.195 ± 0.005	0.206 ± 0.031	0.187 ± 0.022	0.217 ± 0.055	0.157 ± 0.006	0.158 ± 0.002	0.173 ± 0.04	0.163 ± 0.006
WmiSat	Kg_{water}/Kg_{soil}	0.029 ± 0.023	0.153 ± 0.056	0.178 ± 0.021	0.207 ± 0.059	0.091 ± 0.018	0.092 ± 0.02	0.091 ± 0.017	0.102 ± 0.024
Wmasat	Kg_{water}/Kg_{soil}	0.167 ± 0.023	0.052 ± 0.06	0.01 ± 0.001	0.009 ± 0.01	0.066 ± 0.012	0.066 ± 0.019	0.083 ± 0.058	0.061 ± 0.019
Emi	Kg_{water}/Kg_{soil}	0.205 ± 0.023	2.498 ± 0.44	2.482 ± 0.557	3.944 ± 2.424	8.213 ± 1.483	9.114 ± 0.39	7.059 ± 1.851	11.298 ± 2.358
WL	Kg_{water}/Kg_{soil}	0.194 ± 0.057	0.195 ± 0.04	0.178 ± 0.018	0.196 ± 0.06	0.142 ± 0.006	0.15 ± 0.005	0.152 ± 0.028	0.149 ± 0.011
Wip	J/Kg_{solids}	0.009 ± 0.008	0.016 ± 0.024	0.001 ± 0.001	0 ± 0	0.013 ± 0.002	0.006 ± 0	0.009 ± 0.005	0.013 ± 0.001
Ema	J/Kg_{solids}	0.582 ± 0.438	0.53 ± 0.831	0.022 ± 0.032	0.001 ± 0	0.265 ± 0.097	0.077 ± 0.034	0.236 ± 0.117	0.348 ± 0.094
Kbs	dm^3/Kg_{water}	0.022 ± 0.02	0.018 ± 0.004	0.007 ± 0.007	0.011 ± 0.004	0.064 ± 0.017	0.051 ± 0.055	0.043 ± 0.003	0.045 ± 0.025
Kst	dm^3/Kg_{water}	0.004 ± 0.004	0.001 ± 0.001	0.014 ± 0.016	0.069 ± 0.054	0.317 ± 0.55	0.167 ± 0.244	0.318 ± 0.548	0.131 ± 0.227
Kip	dm^3/Kg_{water}	0.449 ± 0.655	0.4 ± 0.693	1.2 ± 0	0.831 ± 0.639	0.616 ± 0.524	0.149 ± 0.258	0.718 ± 0.63	0.539 ± 0.601
V0	dm^3/Kg_{soil}	0.627 ± 0.039	0.656 ± 0.006	0.654 ± 0.026	0.675 ± 0.024	0.605 ± 0.011	0.631 ± 0.023	0.638 ± 0.037	0.628 ± 0.017
ΔShC	dm^3/Kg_{soil}	0.007 ± 0.002	0.005 ± 0.002	0.011 ± 0.002	0.008 ± 0.003	0.007 ± 0.003	0.006 ± 0.004	0.016 ± 0.014	0.008 ± 0.002
AW	(Kg_{water}/Kg_{soil})	0.006 ± 0.005	0.154 ± 0.036	0.151 ± 0.033	0.167 ± 0.028	0.071 ± 0.022	0.064 ± 0.022	0.069 ± 0.042	0.085 ± 0.037